Overview of DIS results, global fittings and DY predictions

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Outline

- Brief introduction
  - SSA theory
  - Sign change

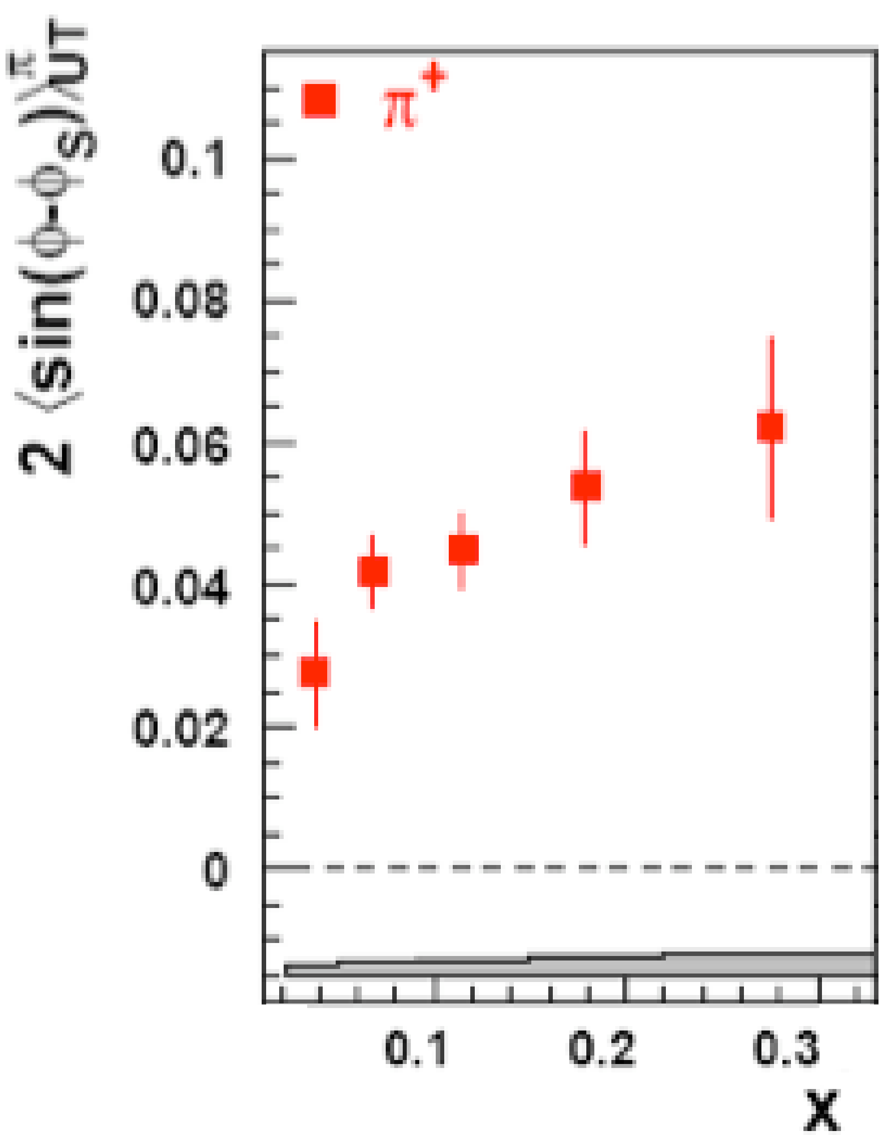
- Sivers function and current predictions
  - Global fitting from SIDIS
  - Predictions for DY
  - Some other channels

- Consequence of DY measurements

Experimental data on single transverse spin asymmetry

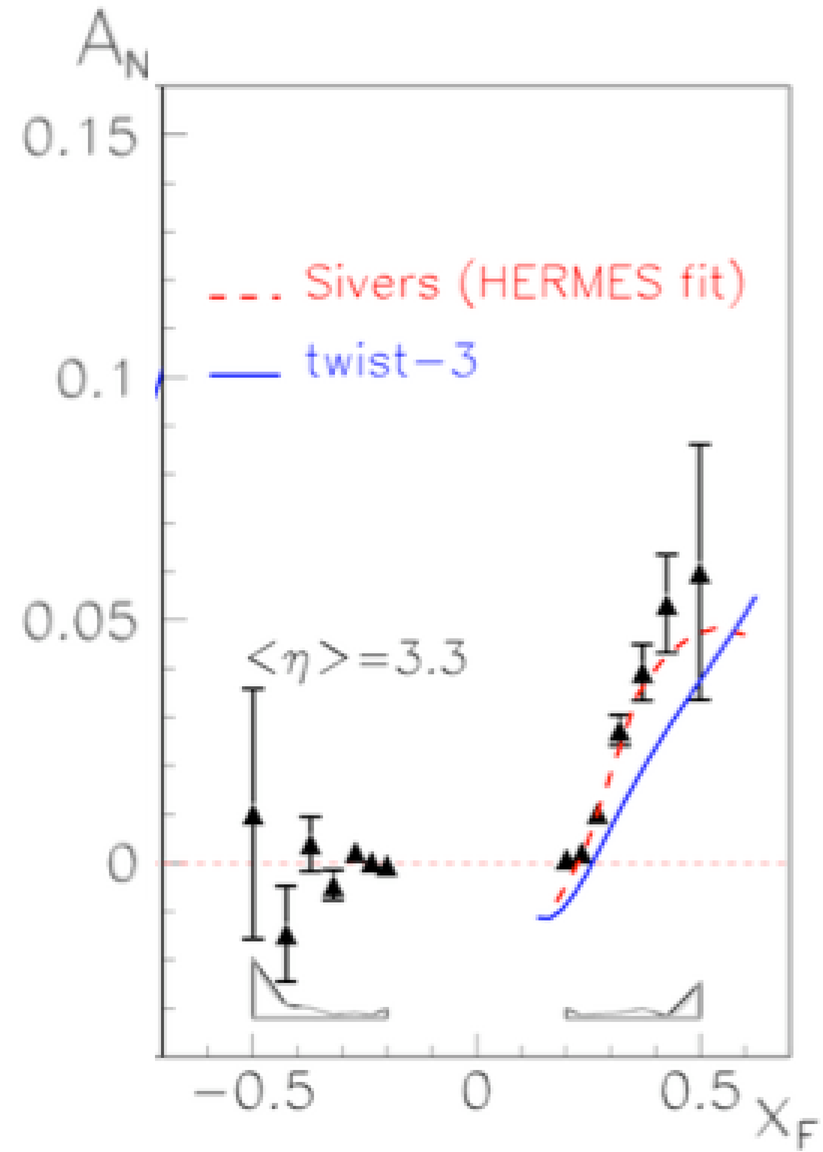
- Single transverse spin asymmetries (SSAs) have been observed in various experiments at different CM energies
  - PHENIX, BRAHMS, COMPASS, JLAB, too

$$A_N \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s}) - \sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s}) + \sigma(\ell,-\vec{s})}$$



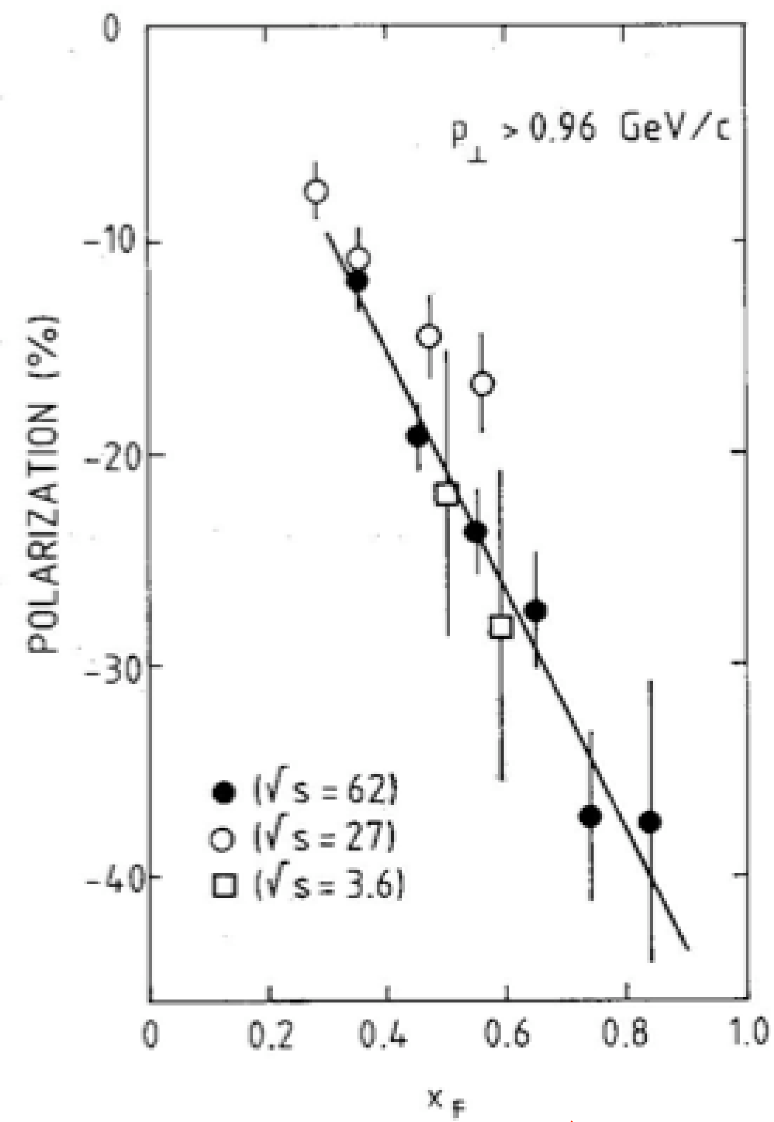
$\ell + p^{\uparrow} \to \ell' + \pi + X$

HERMES



$p + p^{\uparrow} \to \pi + X$

STAR



$p + p \to \Lambda^{\uparrow} + X$

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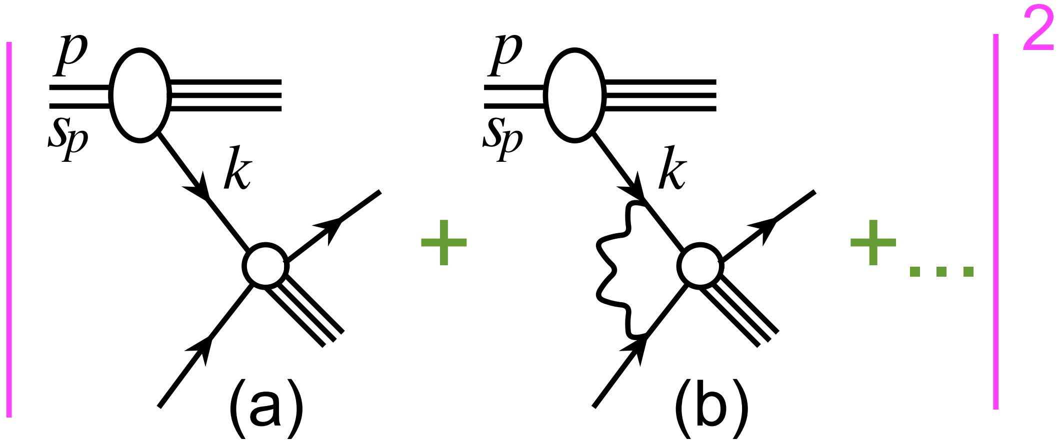
SSA vanishes at leading twist in collinear factorization

- At leading twist formalism: partons are collinear

Kane, Pumplin, Repko, 1978

$\sigma(s_T) \sim$  $\Rightarrow \Delta\sigma(s_T) \sim \mathrm{Re}[(a)]\cdot\mathrm{Im}[(b)]$

  - generate phase from loop diagrams, proportional to α_s
  - helicity is conserved for massless partons, helicity-flip is proportional to current quark mass m_q

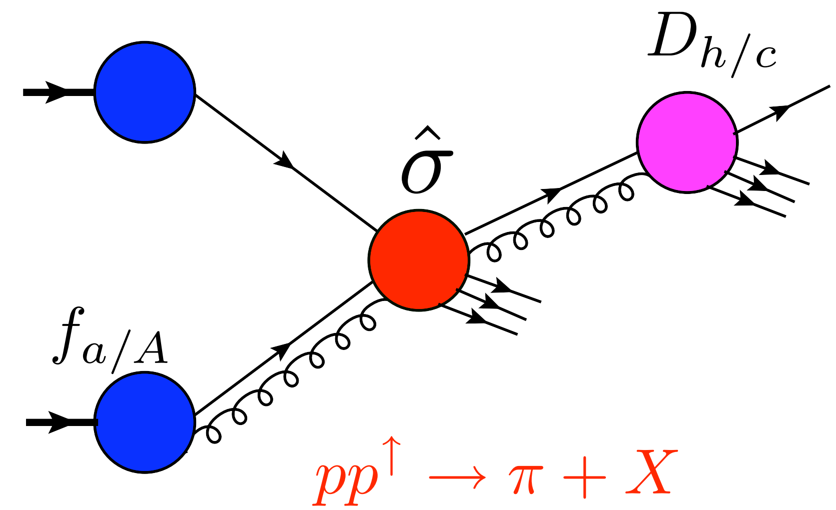
  Therefore we have

$$A_N \sim \alpha_s \frac{m_q}{\sqrt{s}} \to 0$$

- $A_N \neq 0$: result of parton's transverse motion or correlations!

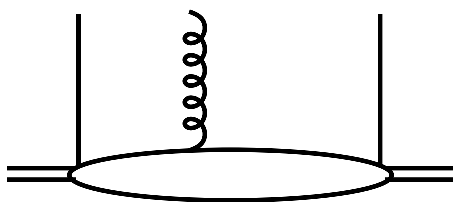
Two mechanisms to generate SSA in QCD

- Collinear twist-3 factorization approach

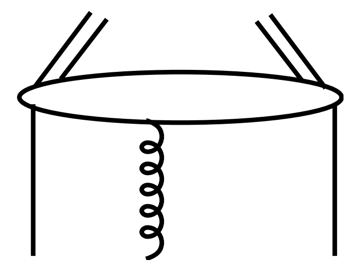


$$\sigma(p_h, s_\perp) \propto f_{a/A}^{s_\perp}(x) \otimes D_{h/c}(z) \otimes \hat{\sigma}_{\text{parton}}$$

  - Twist-3 three-parton corrlation functions (PDFs)
  - Twist-3 three-parton fragmentation functions



Efremov-Teryaev 82, 84, Qiu-Sterman 91, 98, ...



Koike, 02, Kang, Yuan, Zhou 2010

- TMD approach: Transverse Momentum Dependent distributions probe the parton's intrinsic transverse momentum

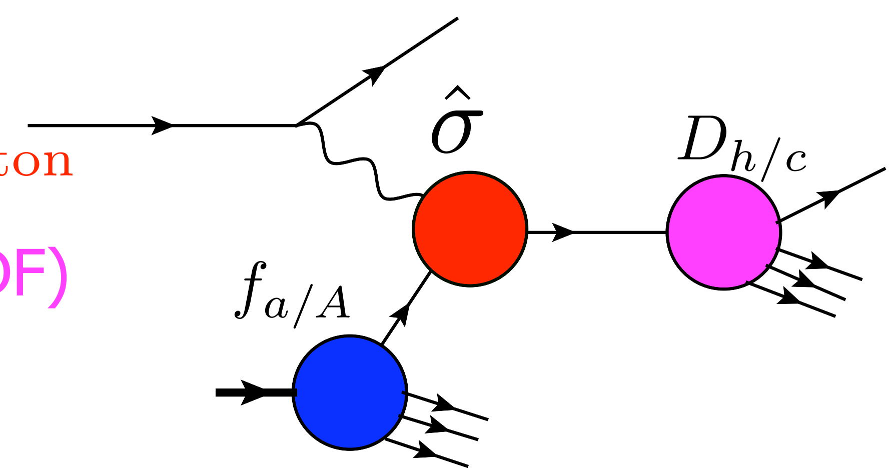
$$\sigma(p_h, s_\perp) \propto f_{a/A}(x, k_\perp) \otimes D_{h/c}(z, p_\perp) \otimes \hat{\sigma}_{\text{parton}}$$

  - Sivers function: in Parton Distribution Function (PDF)

    Sivers 90

  - Collins function: in Fragmentation Function (FF)

    Collins 93



$\ell p^{\uparrow} \to \ell' \pi + X$

Relation between twist-3 and TMD approaches

- They apply in different kinematic domain:
  - TMD approach: need TMD factorization, applies for the process with two observed momentum scales: DY at small Q_T

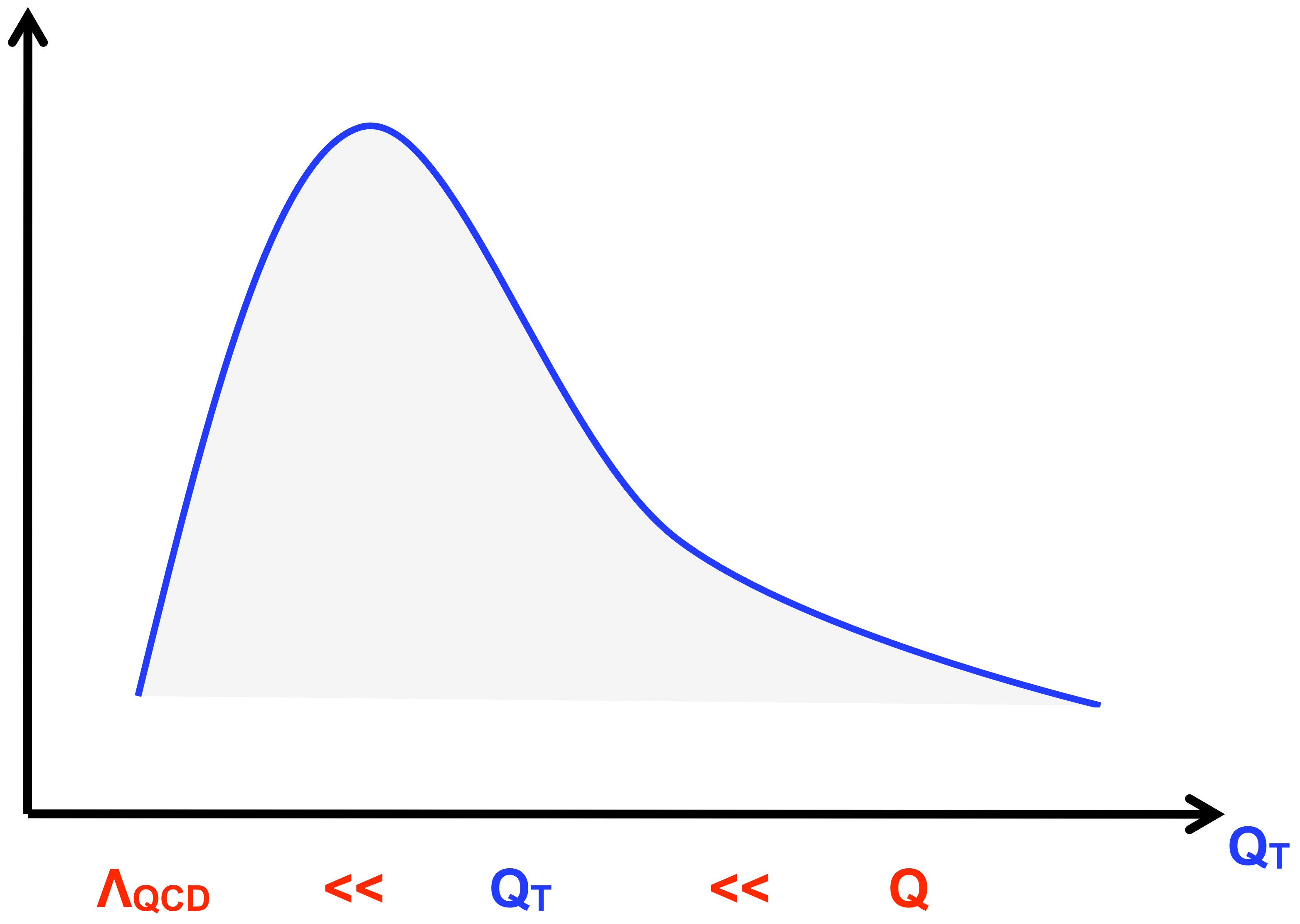
$$Q_1 \gg Q_2 \begin{cases} Q_1 & \text{necessary for pQCD factorization to have a chance} \\ Q_2 & \text{sensitive to parton's transverse momentum} \end{cases}$$

  - Collinear factorization approach: more relevant for single scale hard process: inclusive pion production at pp collision
- They generate same results in the overlap region when they both apply:
  - Twist-3 three-parton correlation in distribution ⟷ Sivers function

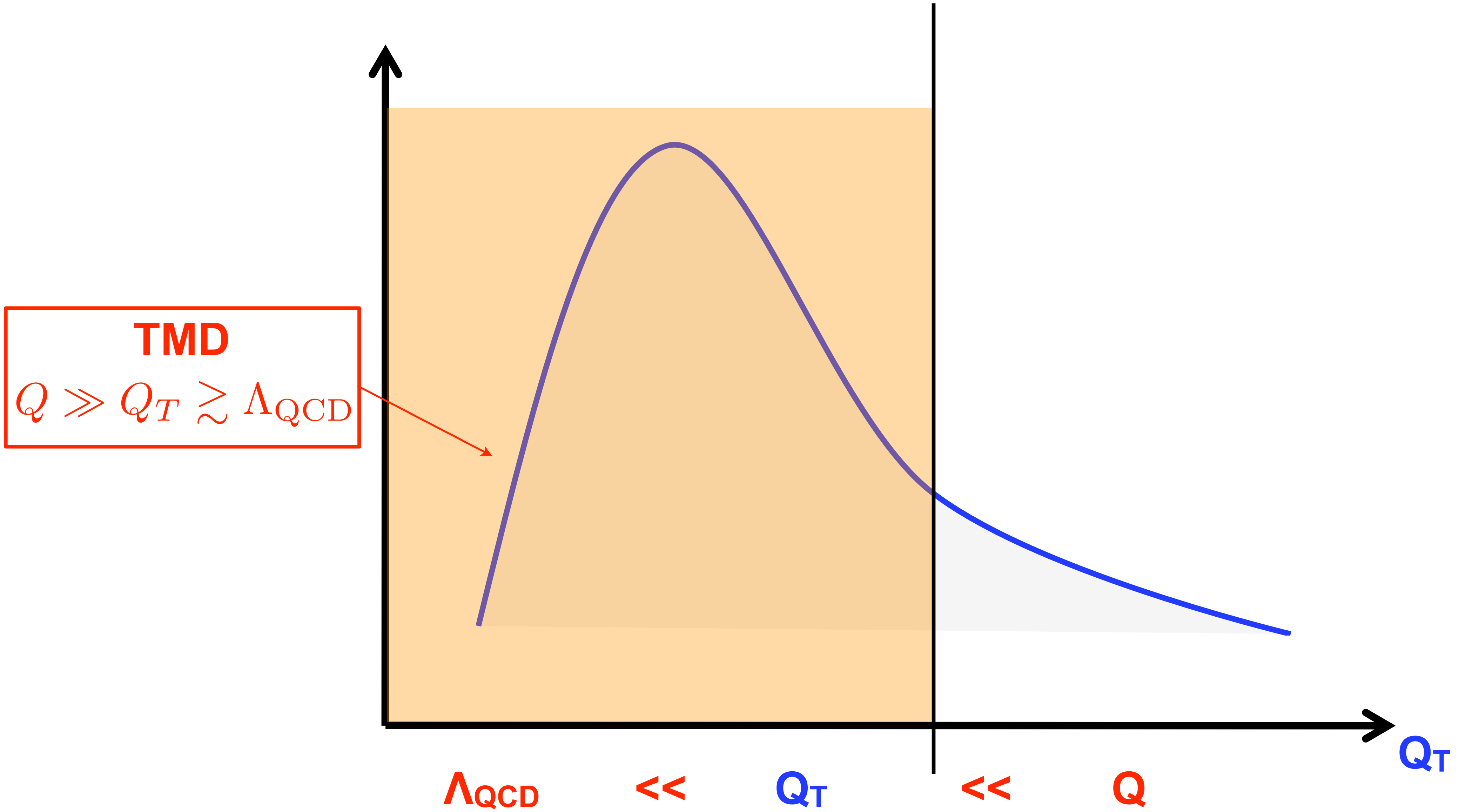
    Ji, Qiu, Vogelsang, Yuan, 2006, ...
  - Twist-3 three-parton correlation in fragmentation ⟷ Collins function

    Zhou, Yuan, 2009, Kang, Yuan, Zhou, 2010

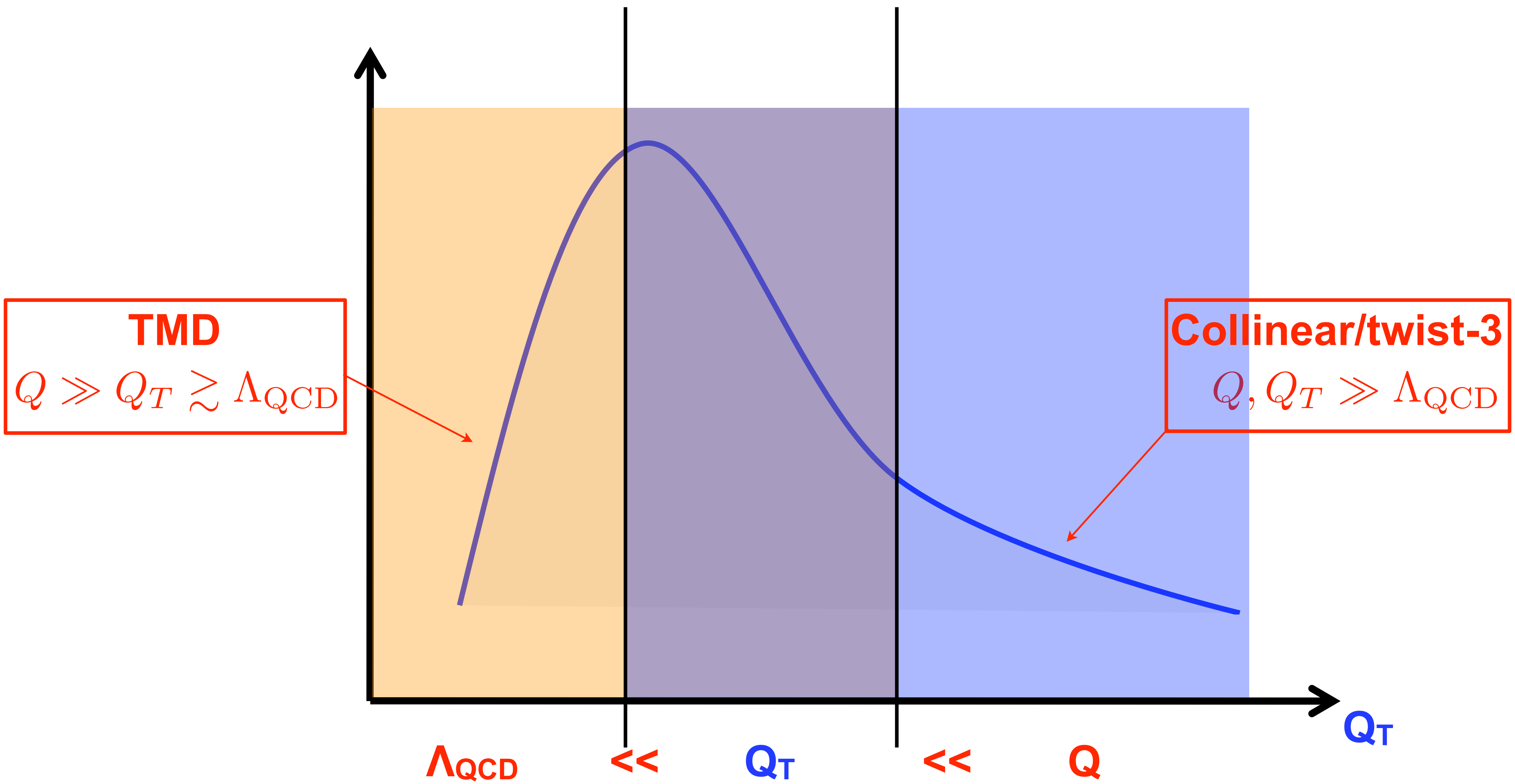
A unified picture for Drell-Yan (leading Q_T/Q)



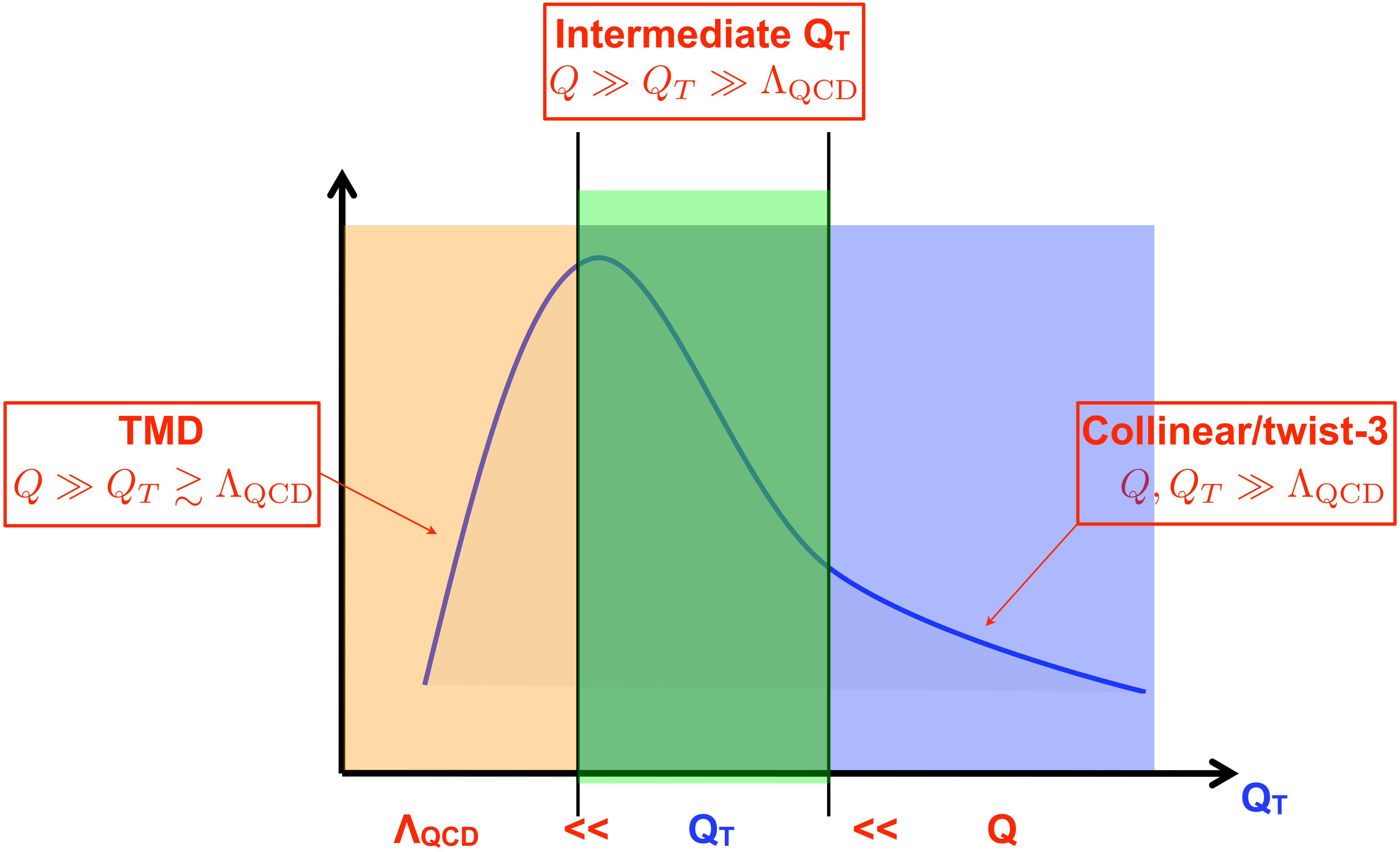
A unified picture for Drell-Yan (leading Q_T/Q)



A unified picture for Drell-Yan (leading Q_T/Q)



A unified picture for Drell-Yan (leading Q_T/Q)



Major difference in these two approaches

- Collinear factorization approach:
  - All the twist-3 correlation functions (both in distribution and fragmentation side) are universal
  - Any process-dependent part is in the hard-part, which is calculable
- However, the TMD function in TMD approach MIGHT not be universal
  - Sivers function is NOT universal

    Collins 02, Boer, Mulders, Pijlman, 03, Collins, Metz, 04, Kang, Qiu, 09, ...
  - Collins function is universal

    Metz 02, Collins, Metz, 04, Yuan, 08, Gamberg, Mukerjee, Mulders, 08, Meissner, Metz, 08, Zhou, Yuan, 09, Boer, Kang, Vogelsang, Yuan, 10...

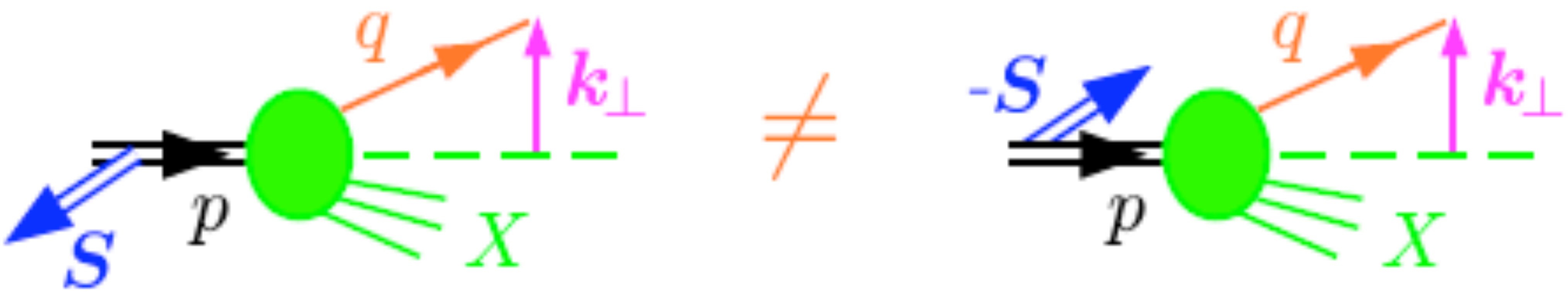
TMD approach: Sivers function

- An asymmetric parton distribution in a polarized hadron (kt correlated with the spin of the hadron)

Spin-dependent

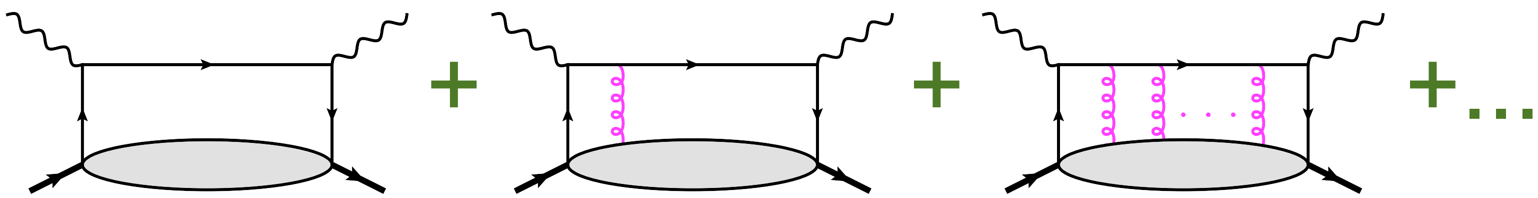
$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) \equiv f_{q/h}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/h^\uparrow}(x,k_\perp)\,\vec{S}\cdot\hat{p}\times\hat{\mathbf{k}}_\perp$$

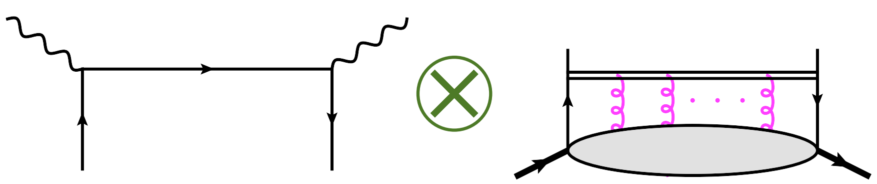
Spin-independent



From experiments to theory: QCD kt-factorization

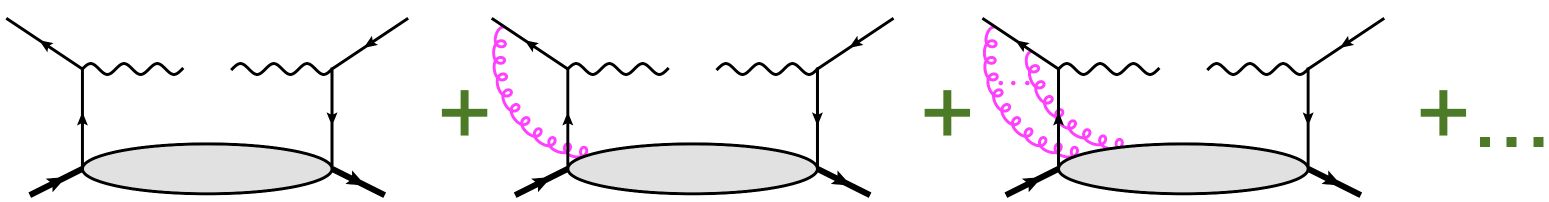
- One measures cross sections in the experiment, and then use theory to connect to the relevant distributions (hadron structure)
  - SIDIS

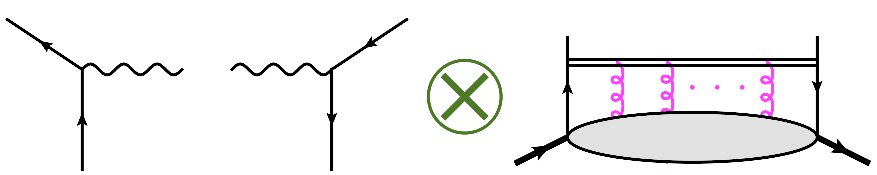
$\sigma \sim$ 

$\approx$ 

PDFs with SIDIS gauge link

  - DY

$\sigma \sim$ 

$\approx$ 

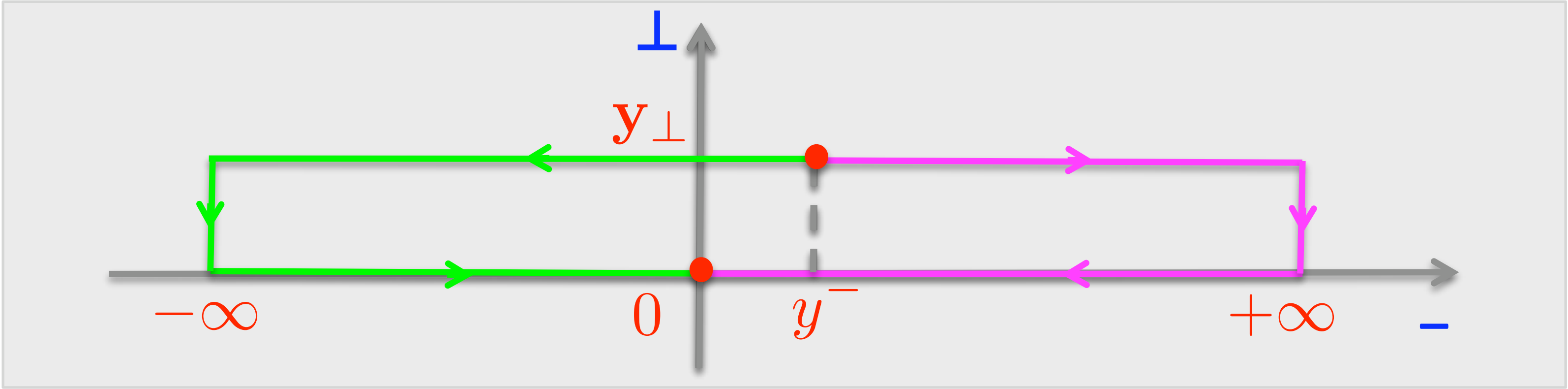
PDFs with DY gauge link

Non-universality of the Sivers function

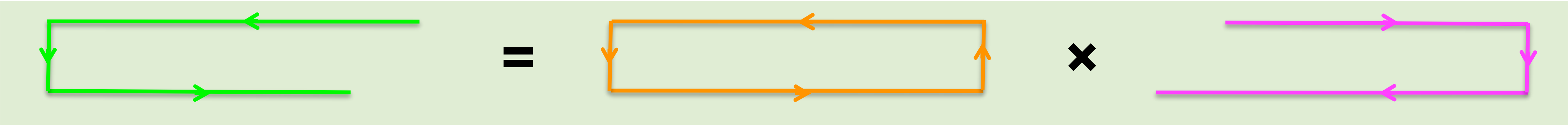
- Different gauge link for gauge-invariant TMD distribution in SIDIS and DY

$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) = \int \frac{dy^- d^2y_\perp}{(2\pi)^3} e^{ixp^+y^- - i\,\mathbf{k}_\perp\cdot\mathbf{y}_\perp} \langle p,\vec{S}|\overline{\psi}(0^-,\mathbf{0}_\perp)\boxed{\text{Gauge link}}\frac{\gamma^+}{2}\psi(y^-,\mathbf{y}_\perp)|p,\vec{S}\rangle$$

  - SIDIS: $\Phi_n^\dagger(\{+\infty,0\},\mathbf{0}_\perp)\Phi_{\mathbf{n}_\perp}^\dagger(+\infty,\{\mathbf{y}_\perp,\mathbf{0}_\perp\})\Phi_n(\{+\infty,y^-\},\mathbf{y}_\perp)$
  - DY: $\Phi_n^\dagger(\{-\infty,0\},\mathbf{0}_\perp)\Phi_{\mathbf{n}_\perp}^\dagger(-\infty,\{\mathbf{y}_\perp,\mathbf{0}_\perp\})\Phi_n(\{-\infty,y^-\},\mathbf{y}_\perp)$



Wilson Loop ~ $\exp\left[-ig\int_\Sigma d\sigma^{\mu\nu}F_{\mu\nu}\right]$ Area is NOT zero



- For a fixed spin state:

$$f_{q/h^\uparrow}^{\text{SIDIS}}(x,\mathbf{k}_\perp,\vec{S}) \neq f_{q/h^\uparrow}^{\text{DY}}(x,\mathbf{k}_\perp,\vec{S})$$

Time-reversal modified universality of the Sivers function

- Relation between Sivers functions in SIDIS and DY
  - From P and T invariance:

$$f_{q/h^\uparrow}^{\rm SIDIS}(x,\mathbf{k}_\perp,\vec{S}) = f_{q/h^\uparrow}^{\rm DY}(x,\mathbf{k}_\perp,-\vec{S})$$

    - **Spin-averaged parton distribution function is universal**

$$f_{q/h}(x,k_\perp) = \frac{1}{2}\left[f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) + f_{q/h^\uparrow}(x,\mathbf{k}_\perp,-\vec{S})\right]$$

  - From the definition of Sivers function:

$$\Delta^N f_{q/h^\uparrow}(x,k_\perp)\,\vec{S}\cdot\hat{p}\times\hat{\mathbf{k}}_\perp = f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) - f_{q/h^\uparrow}(x,\mathbf{k}_\perp,-\vec{S})$$

  - One can derive:

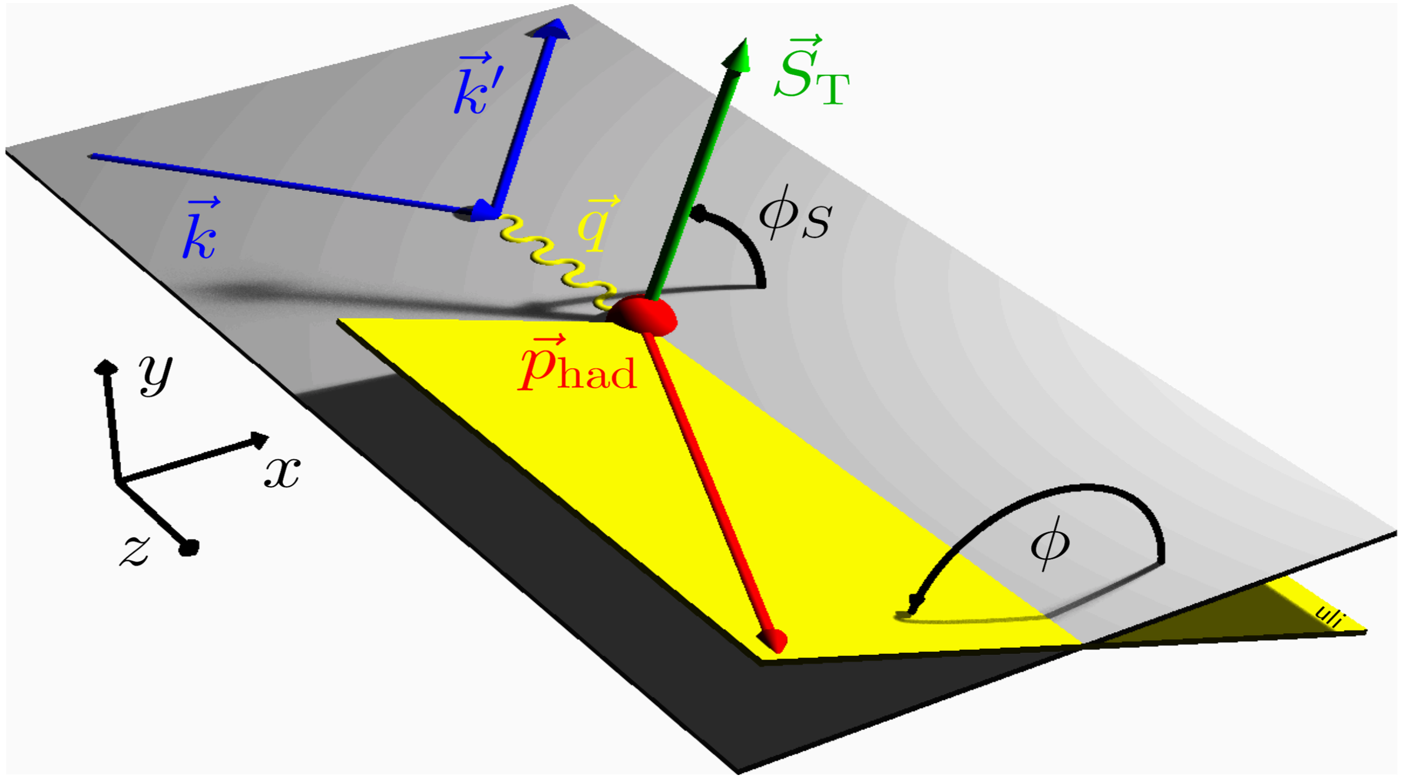
$$\Delta^N f_{q/h^\uparrow}^{\rm SIDIS}(x,k_\perp) = -\Delta^N f_{q/h^\uparrow}^{\rm DY}(x,k_\perp)$$

Most critical test for TMD approach to SSA

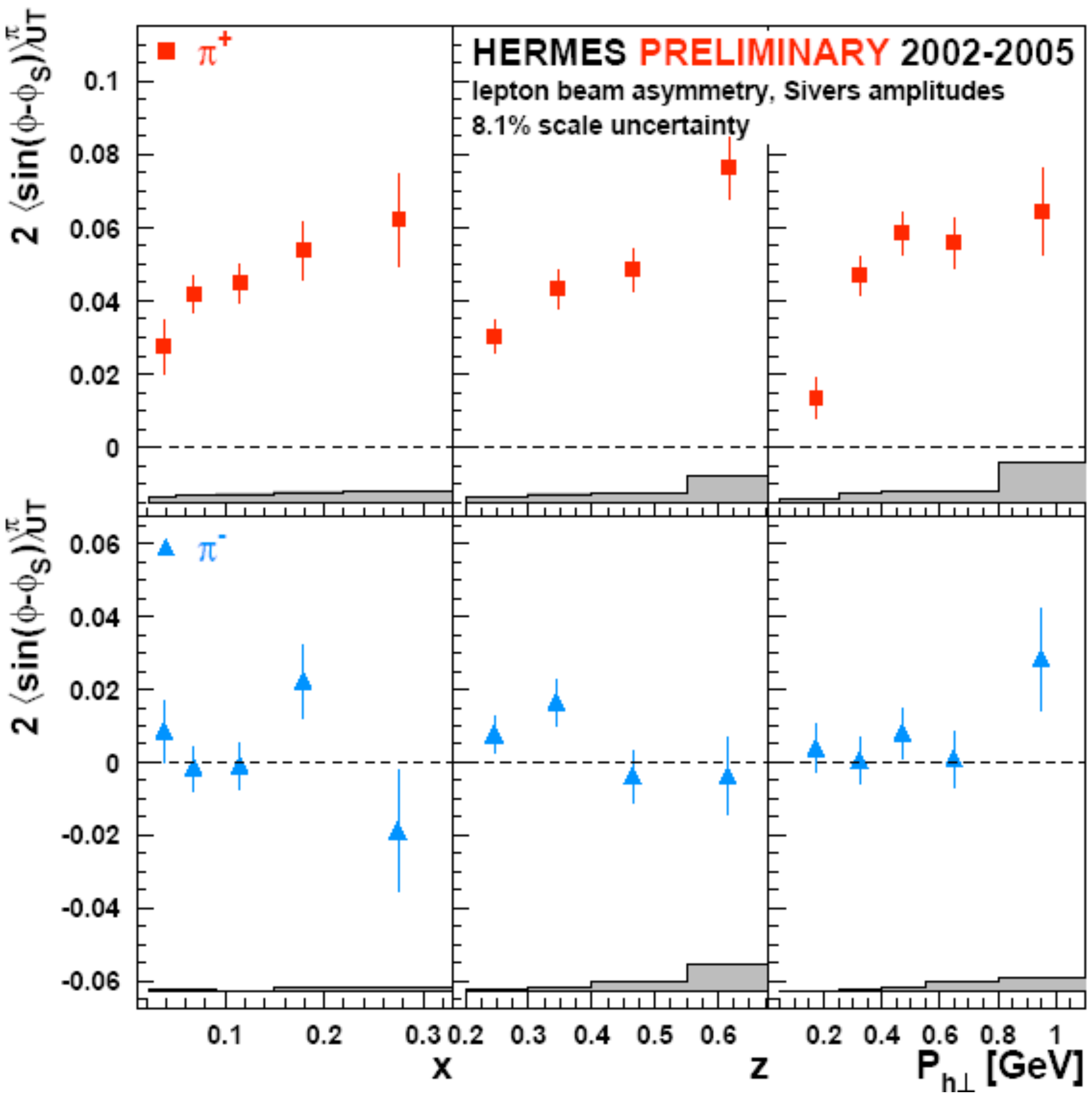
Current Sivers function from SIDIS

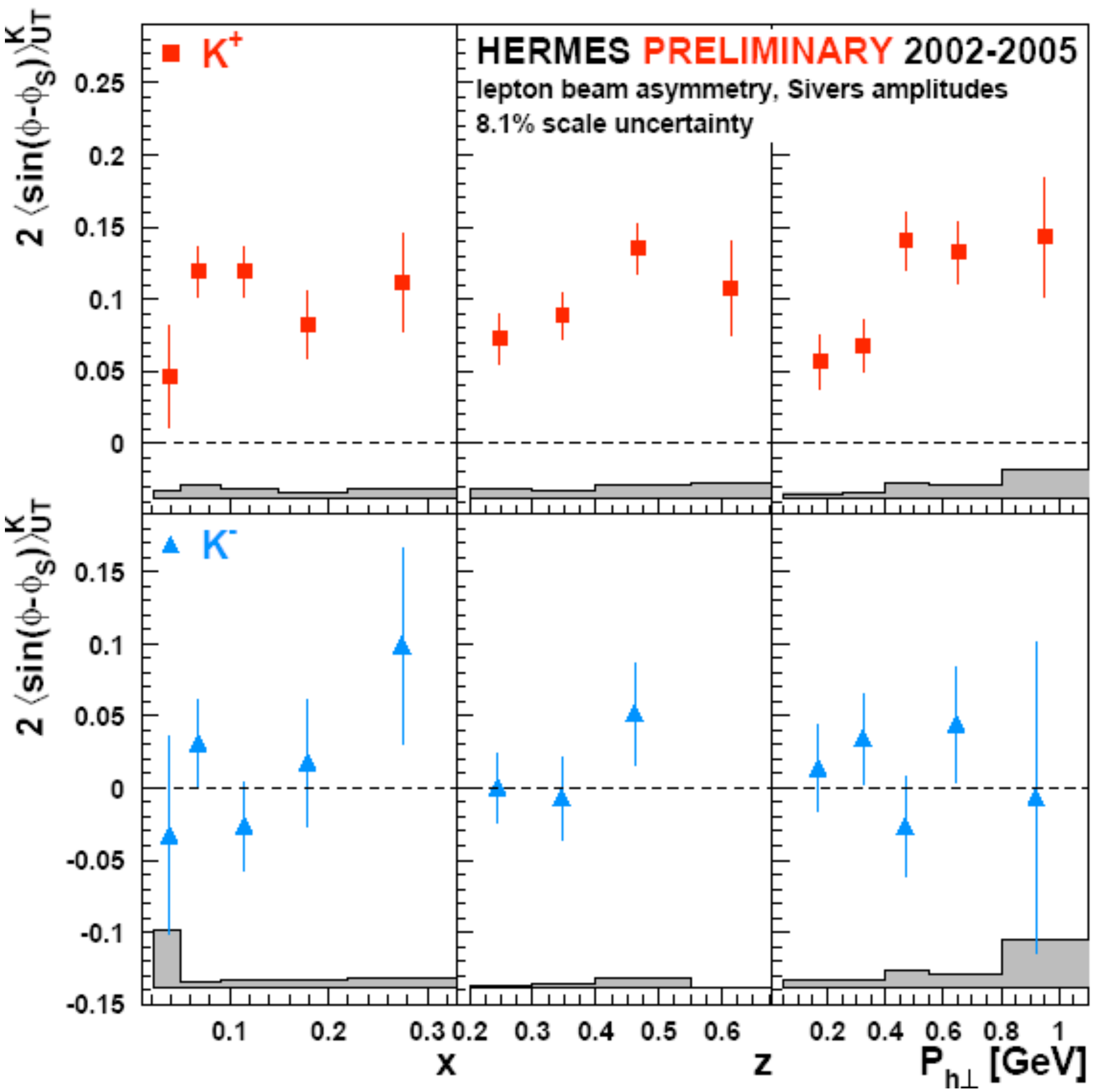
- Sivers and Collins can be separately extracted from SIDIS

$$\Delta\sigma \propto A_{UT}^{\text{Collins}} \sin(\phi + \phi_S) + A_{UT}^{\text{Sivers}} \sin(\phi - \phi_S)$$

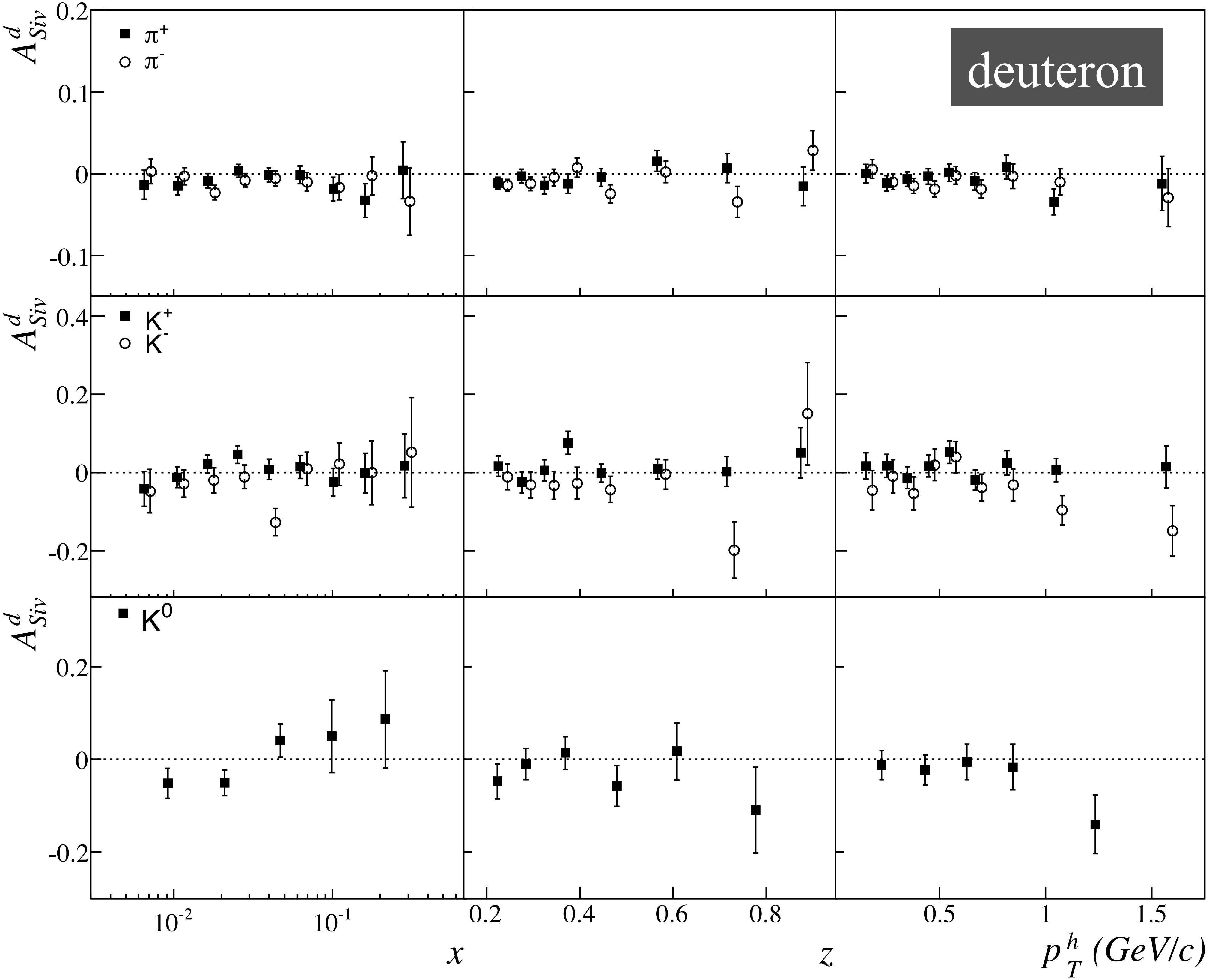


HERMES: Preliminary results on Proton (NOT zero)





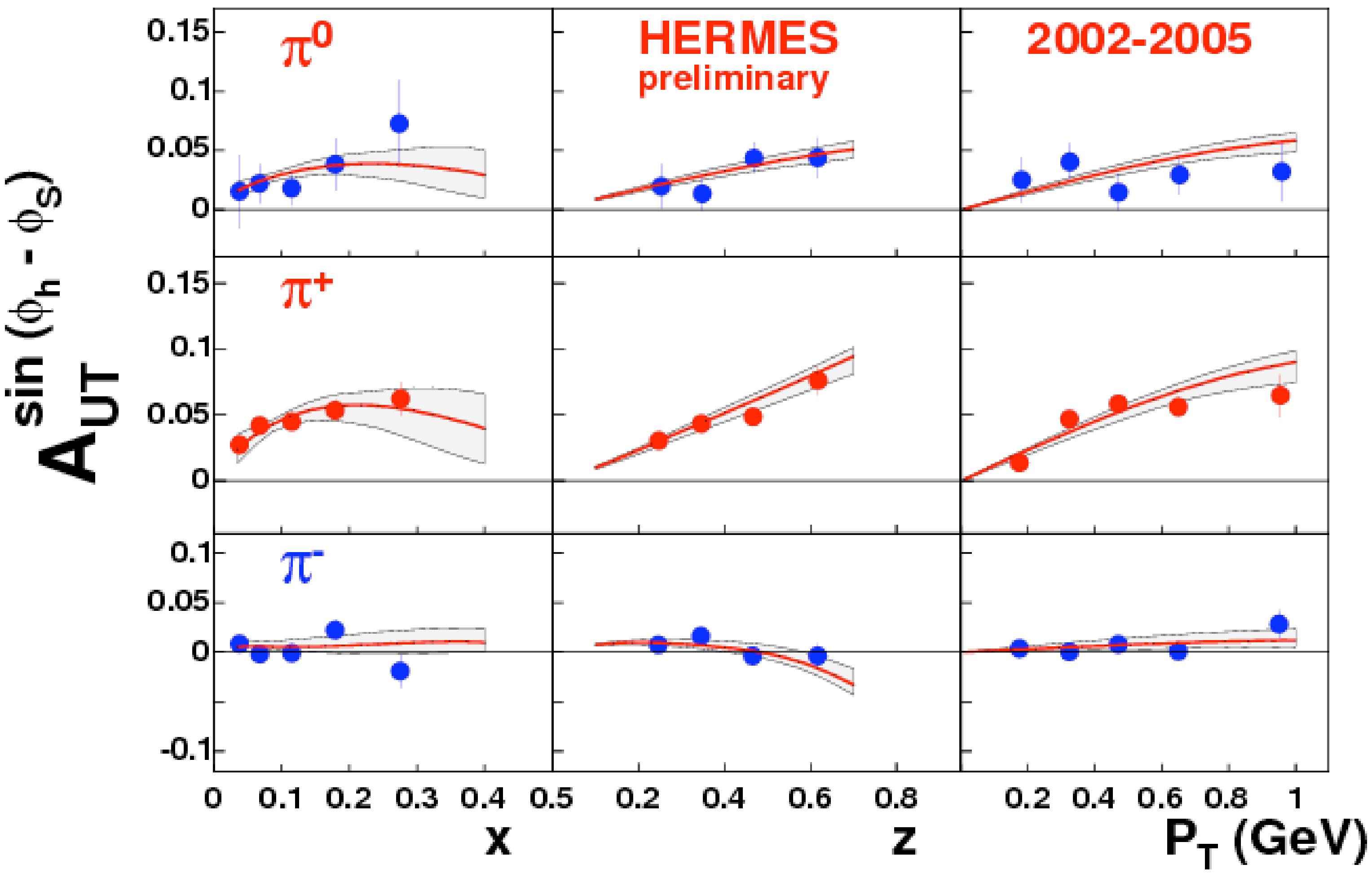
COMPASS: Deuteron target (small or zero)

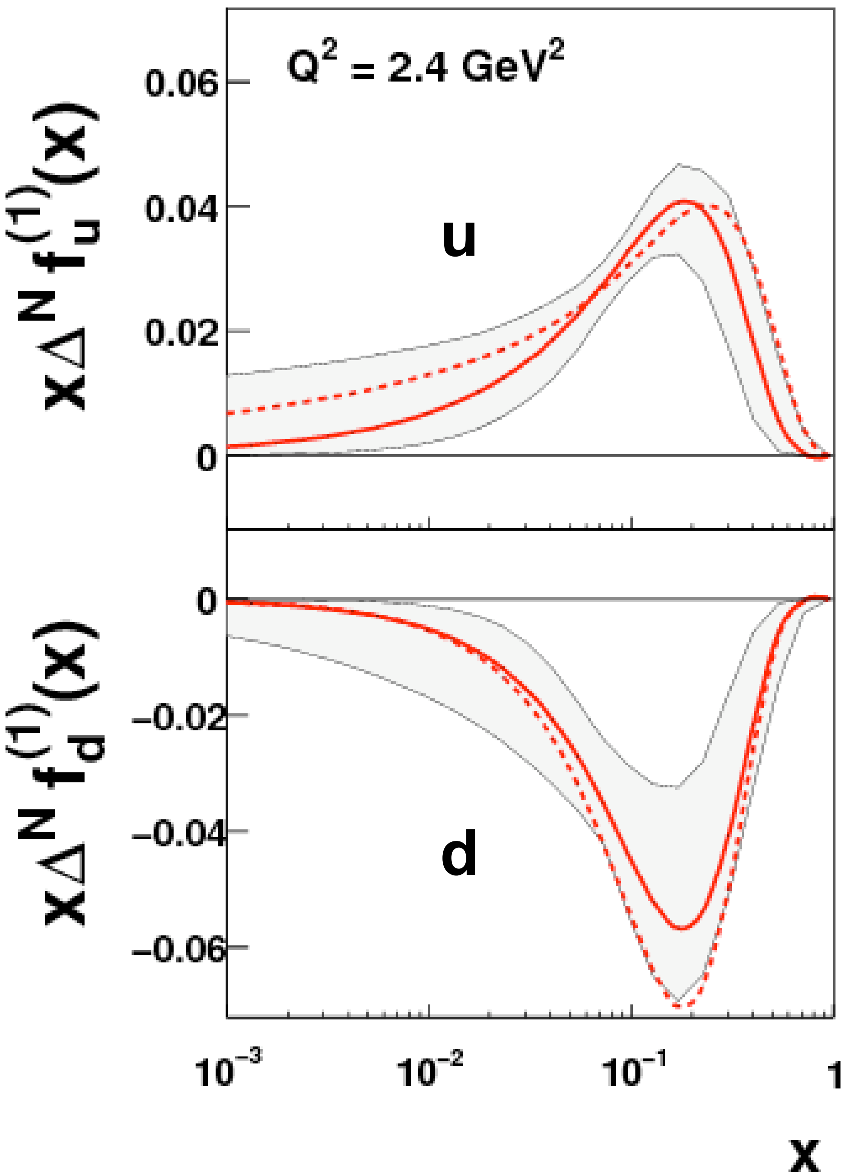


Sivers function from SIDIS: Current Global Analysis

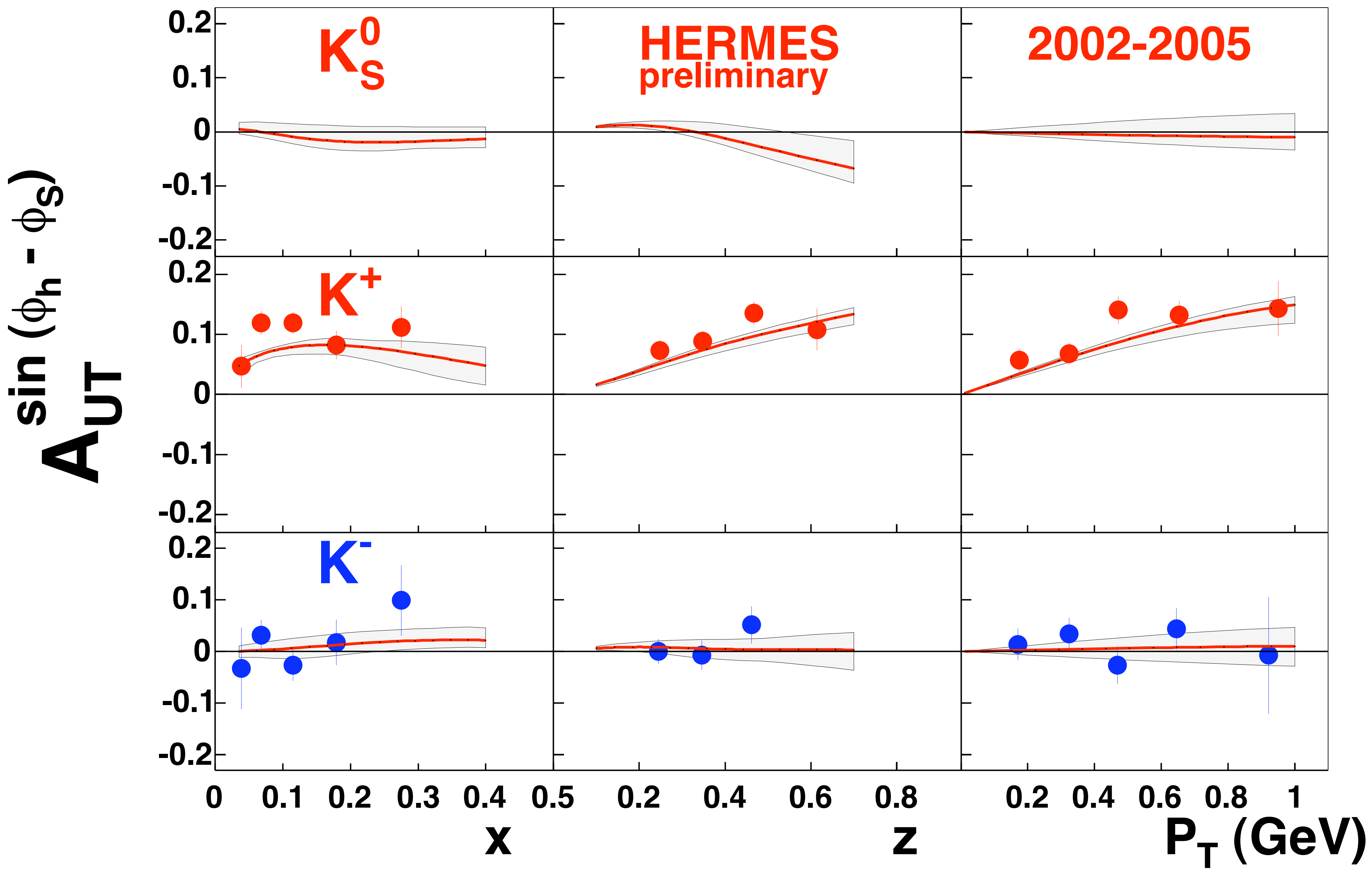
- Includes HERMES Proton data and COMPASS Deuteron data

Anselmino, et.al., 2009

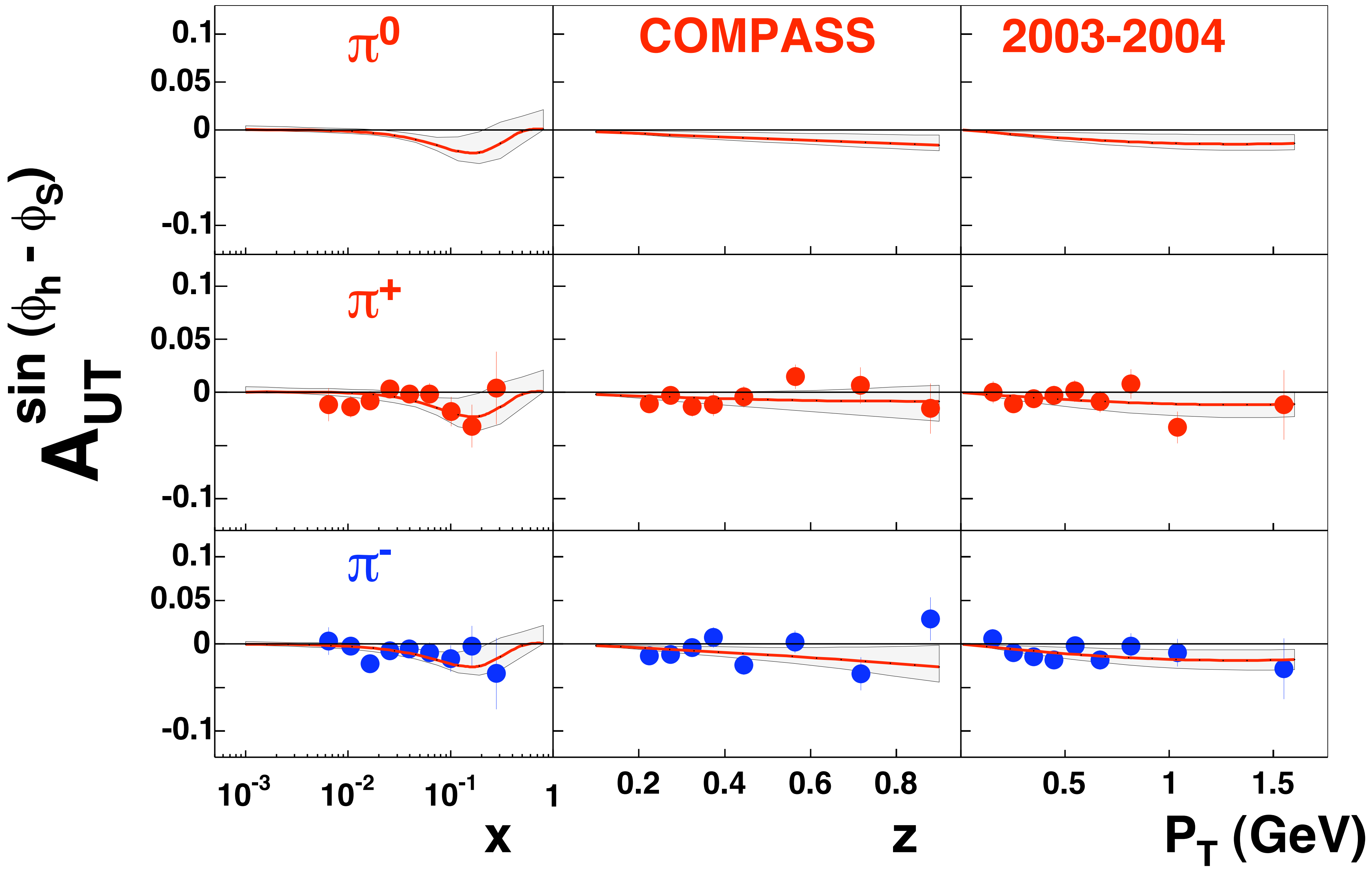




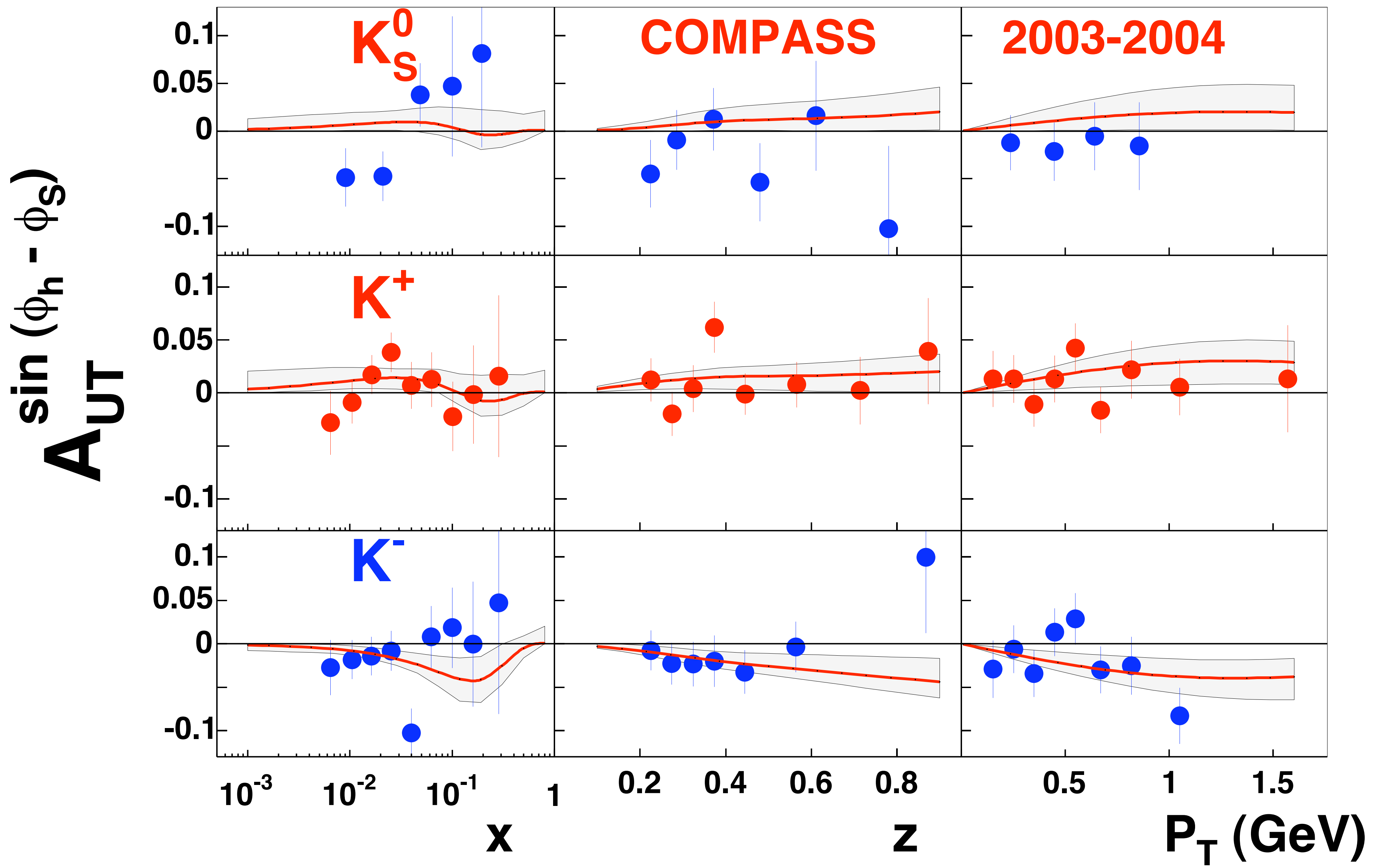
Comparison with HERMES Proton: Kaons



Comparison with COMPASS Deutron: Pions

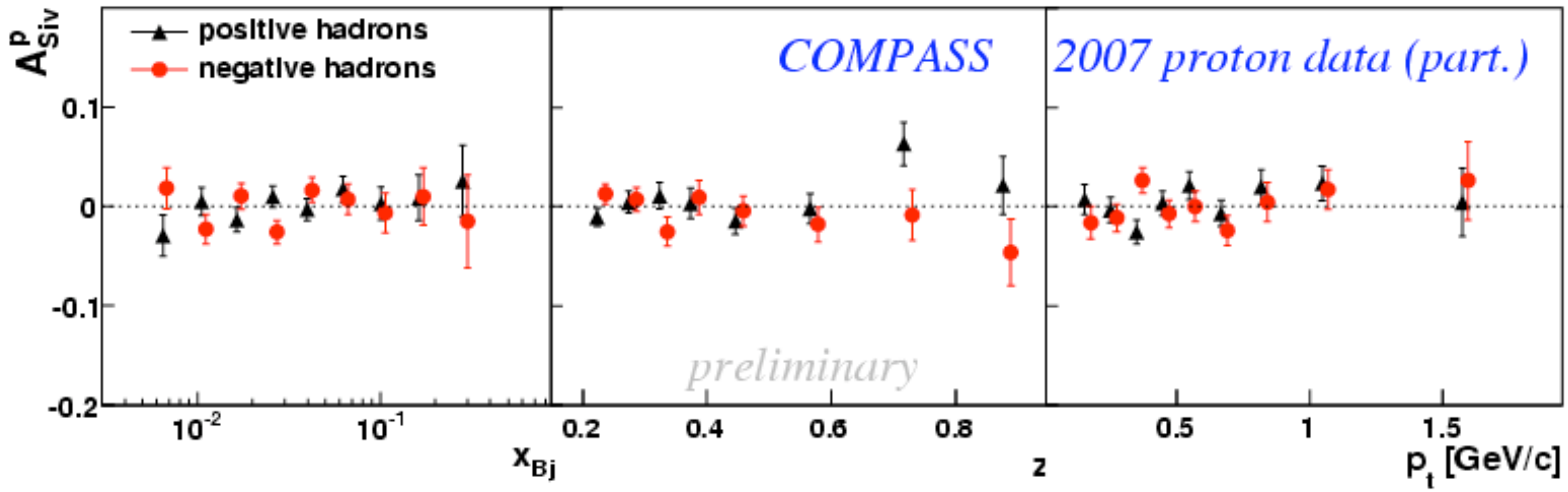


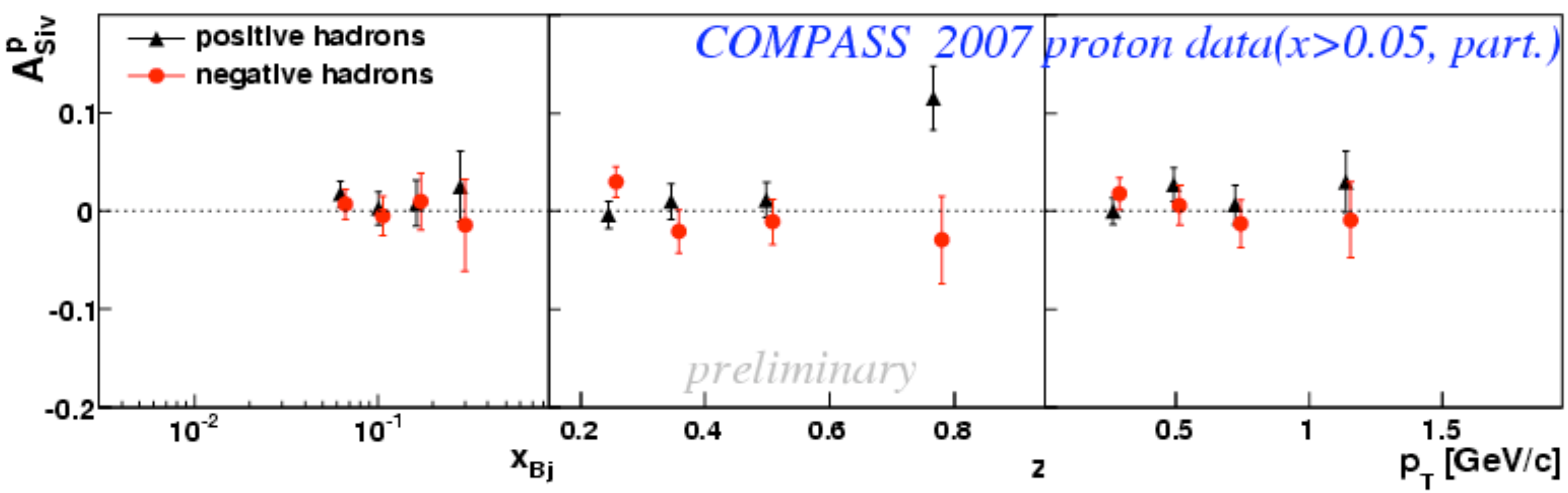
Comparison with COMPASS Deuteron: Kaons



What about COMPASS proton?

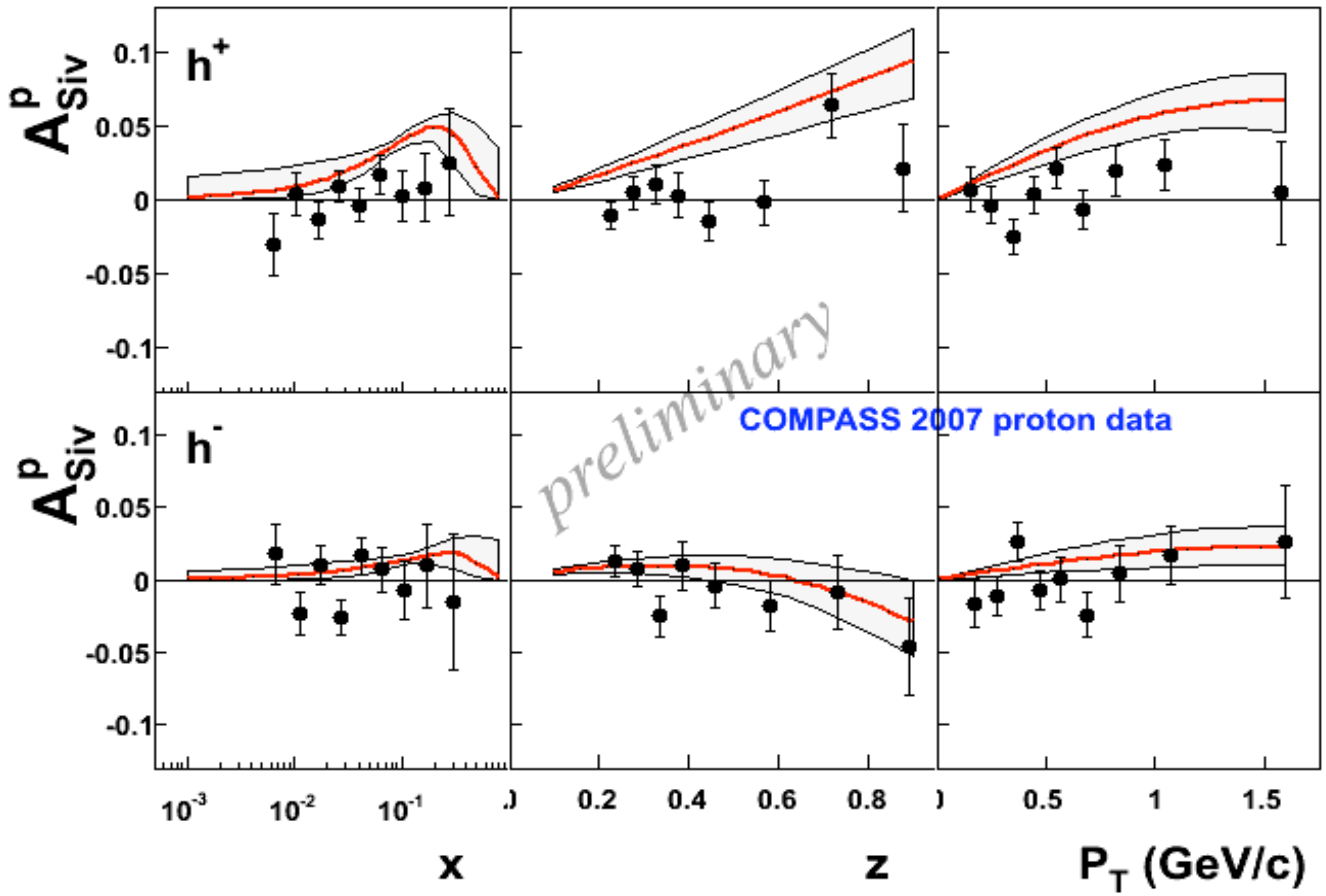
COMPASS: proton (small or zero)





COMPASS Proton compare with theory

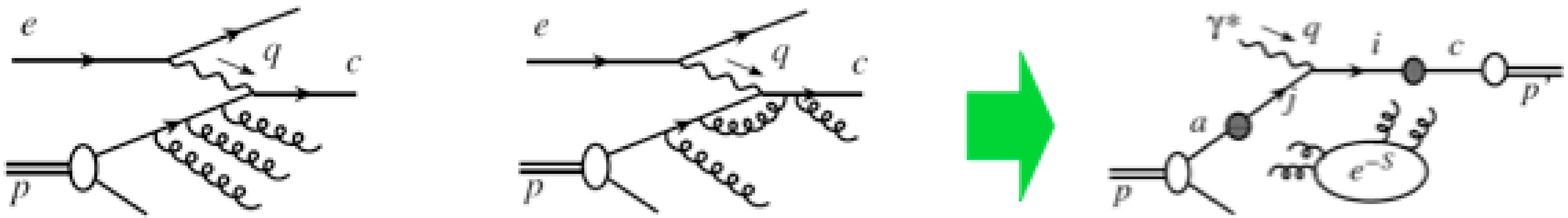
- The predictions do not seem to be consistent with COMPASS proton



- Incompatible between HERMES and COMPASS data on Sivers effect
- Q^2 makes a difference: $\langle Q^2 \rangle \sim 10$ (COMPASS) and 2.4 (HERMES) GeV^2
- QCD resummation?

QCD resummation: Sudakov suppression at high Q^2

- QCD resummation

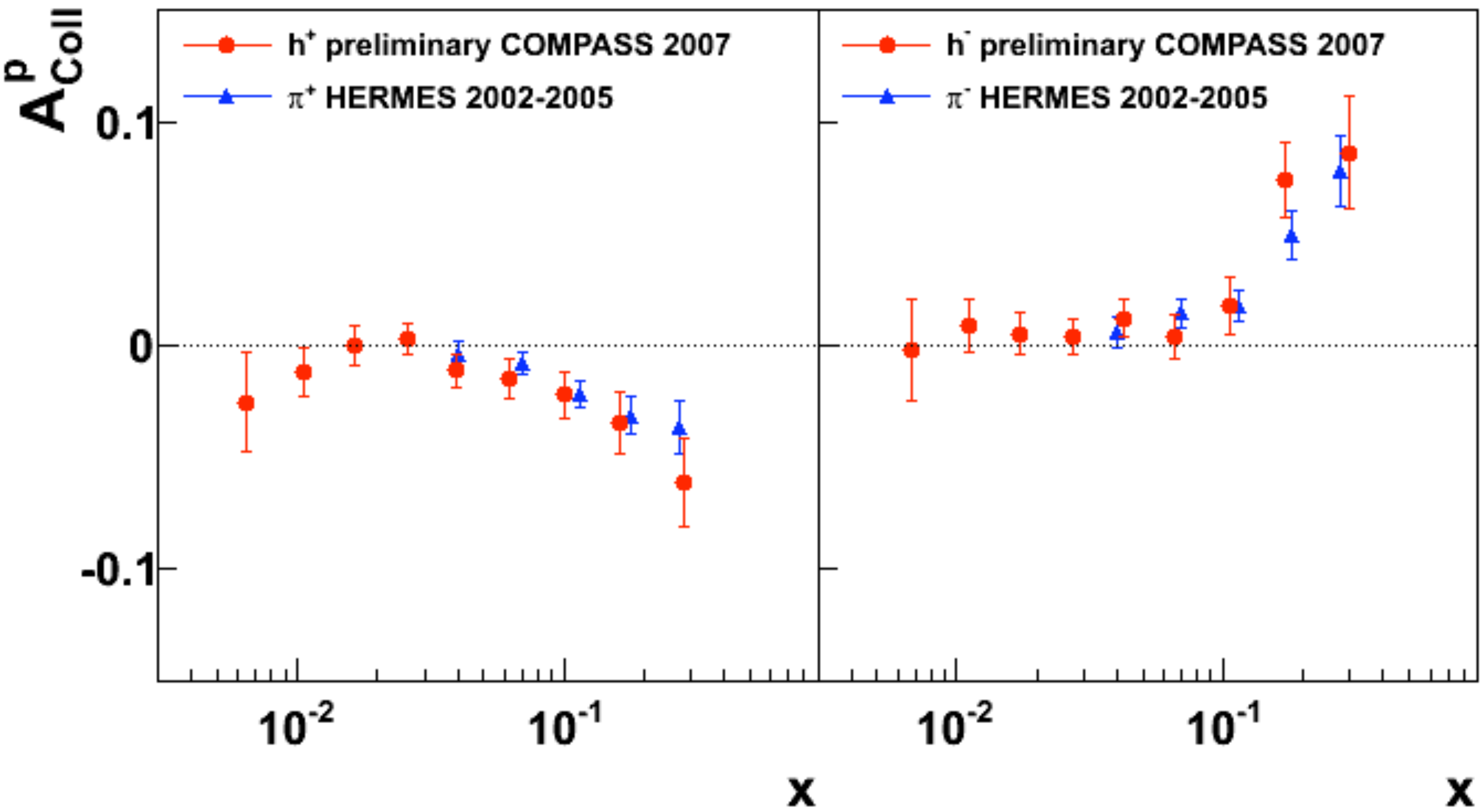


initial-state and final-state soft gluon radiations generate large logarithms: $\frac{1}{q_T^2}\alpha_s^n \log^{2n-1}(Q^2/q_T^2)$

  - Spin-averaged cross section   Collins, Soper, Sterman, 1985, …
  - Spin-dependent cross section (Sivers effect): needs further study
    Boer, 2001
  - More suppressed at higher Q^2

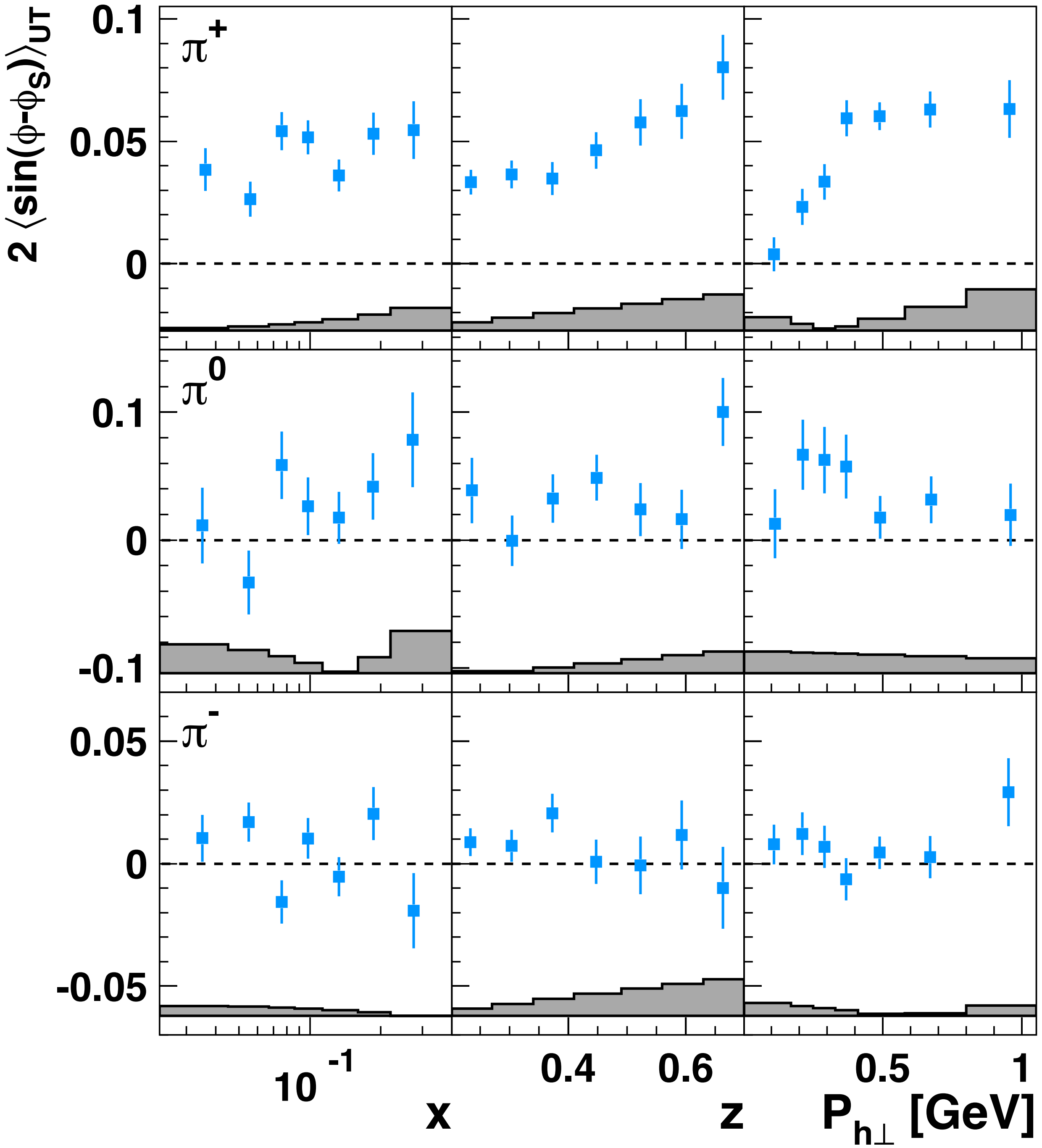
- This effect (Sudakov suppression) is not included in the current formalism when extracting the Sivers functions

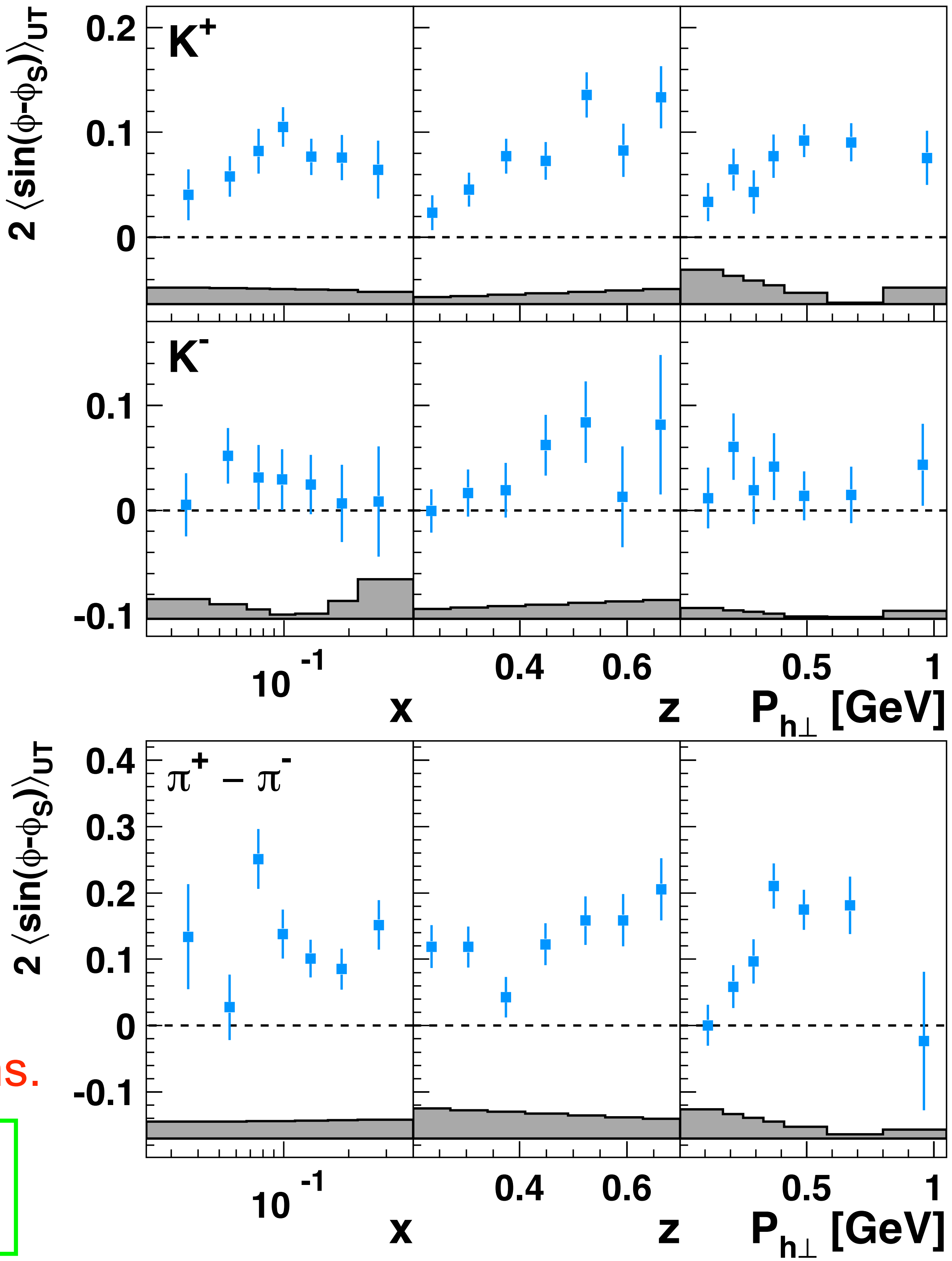
Collins is consistent between COMPASS and HERMES



Final published HERMES Proton: (NOT zero)

HERMES, PRL 103, 152002 (2009)



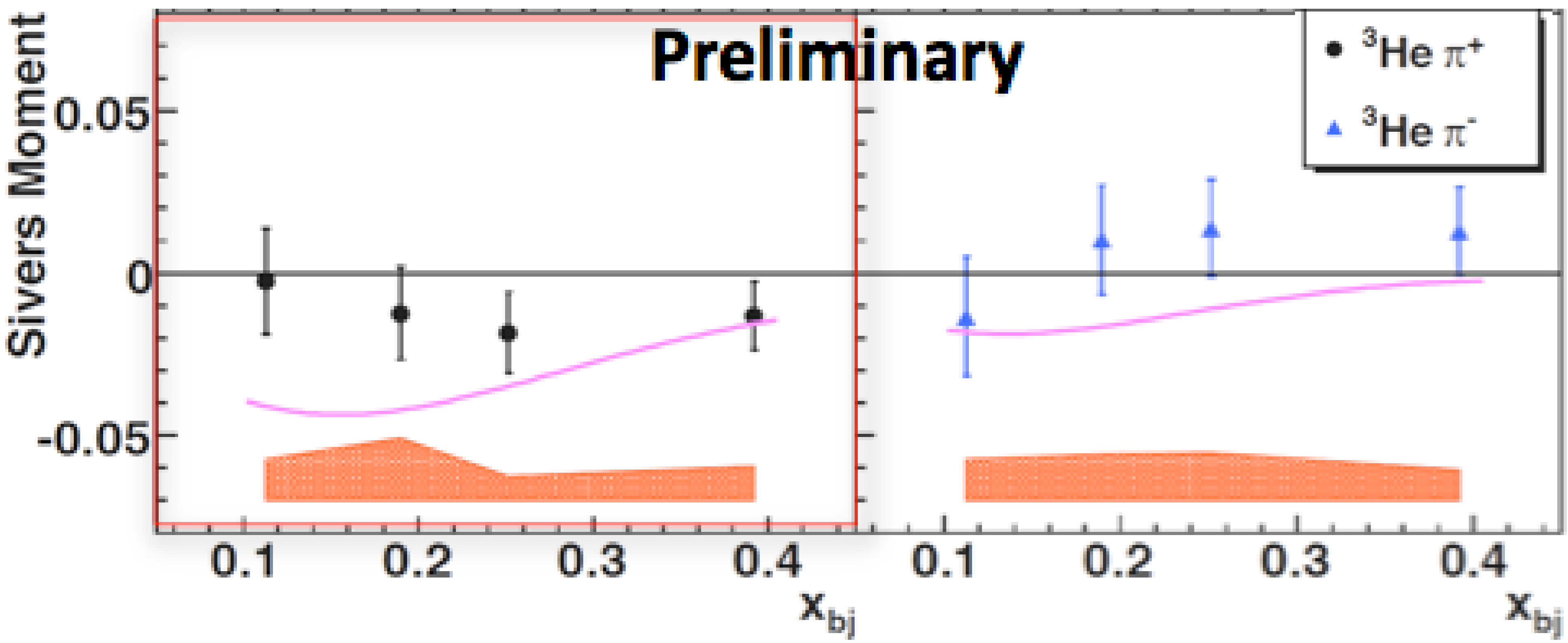


Slight change in data, main message remains.

Problem with the parametrization of global analysis?

Sign difference between u and d Sivers functions

- u and d Sivers functions have opposite sign
  - For proton, pi+ > 0, then for neutron, pi+ < 0
  - At the same time, pi- for neutron should be smaller than pi+
  - JLAB preliminary results

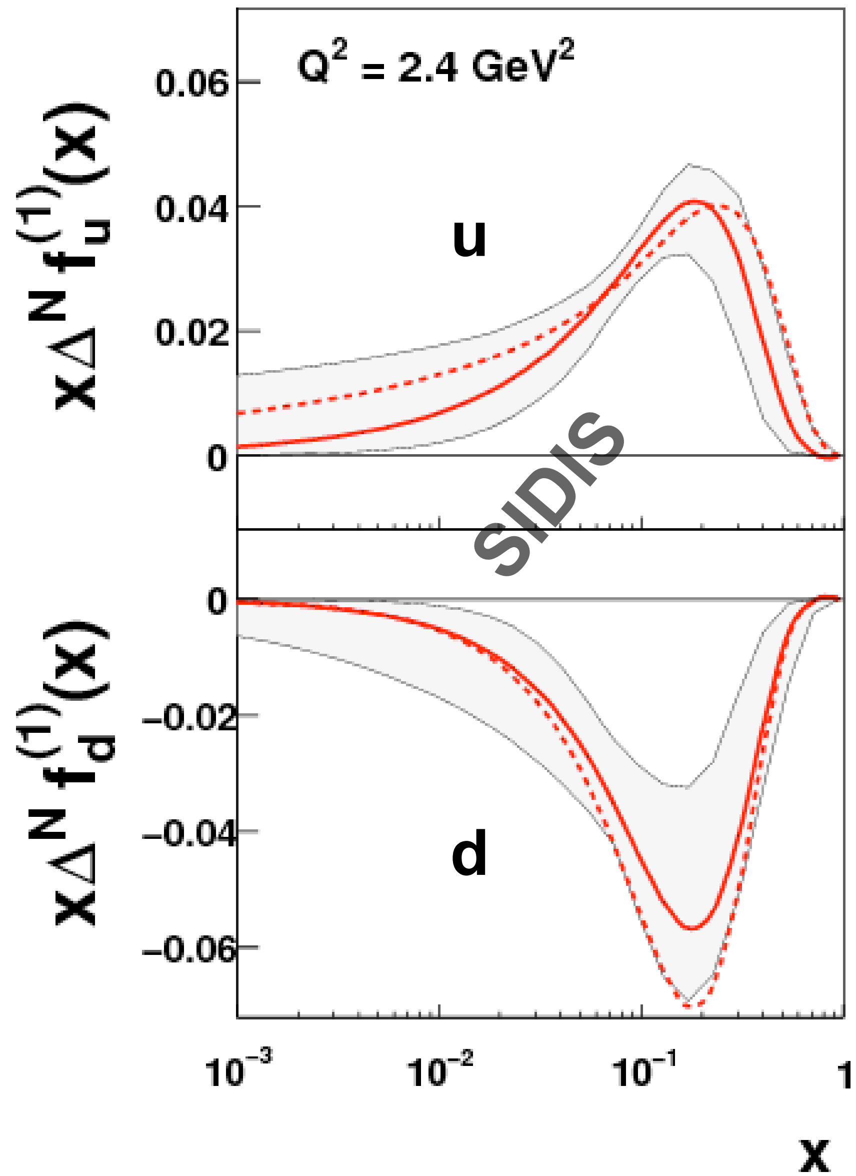


From Xiaodong Jiang's talk TMD 2010

Assume HERMES is correct

- Since theory doesn't prevent the existence of the Siver functions:

SIDIS		DY
$\mathbf{Sivers}_{\mathbf{u-quark}} > 0$	QCD ➡	$\mathbf{Sivers}_{\mathbf{u-quark}} < 0$
$\mathbf{Sivers}_{\mathbf{d-quark}} < 0$		$\mathbf{Sivers}_{\mathbf{d-quark}} > 0$



- u and d almost equal size, different sign
- u-Sivers is slightly smaller than d-Sivers

Sivers effect in Drell-Yan process

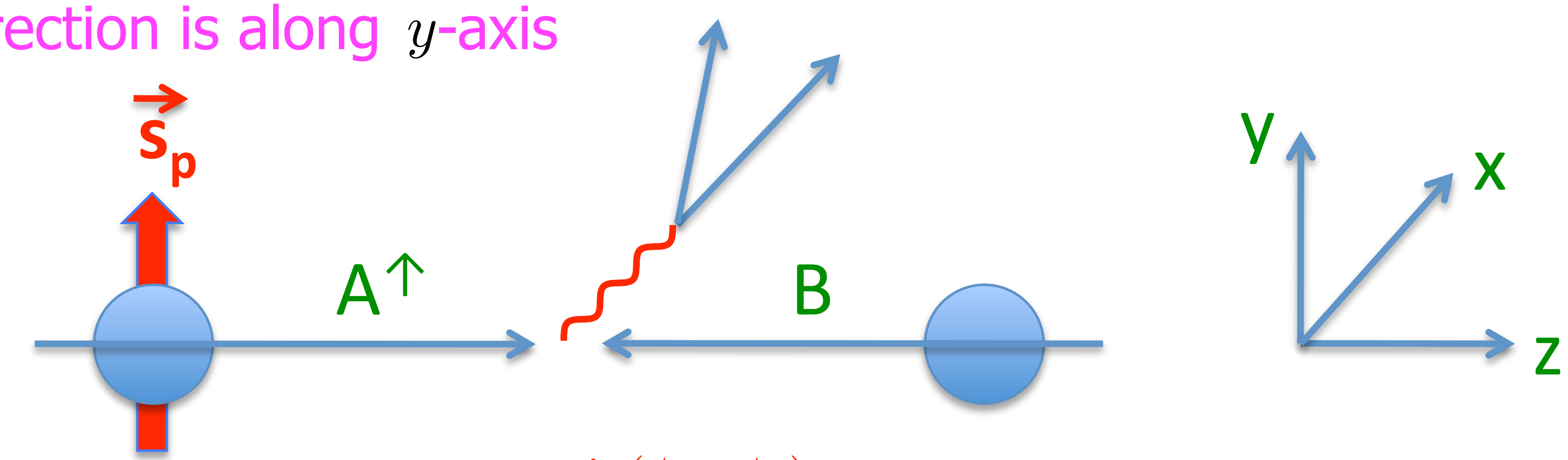
- Formula in TMD approach: weighted sum of u and d-Sivers

$$A_N = \frac{\sum_q e_q^2 \int \Delta^N f_{q/A^\uparrow}(x_1, \mathbf{k}_{\perp 1}) f_{\bar{q}/B}(x_2, k_{\perp 2})}{2\sum_q e_q^2 \int f_{q/A}(x_1, k_{\perp 1}) f_{\bar{q}/B}(x_2, k_{\perp 2})} \propto \frac{4}{9}\Delta^N u + \frac{1}{9}\Delta^N d$$

➡ $A_N < 0$

  - In principle, there could also be contribution from Boer-Mulders functions times transversity: it should be very small, since it involves either anti-quark Boer-Mulders, or anti-quark transversity (or use weighted asymmetry, since they have different angle dependence)

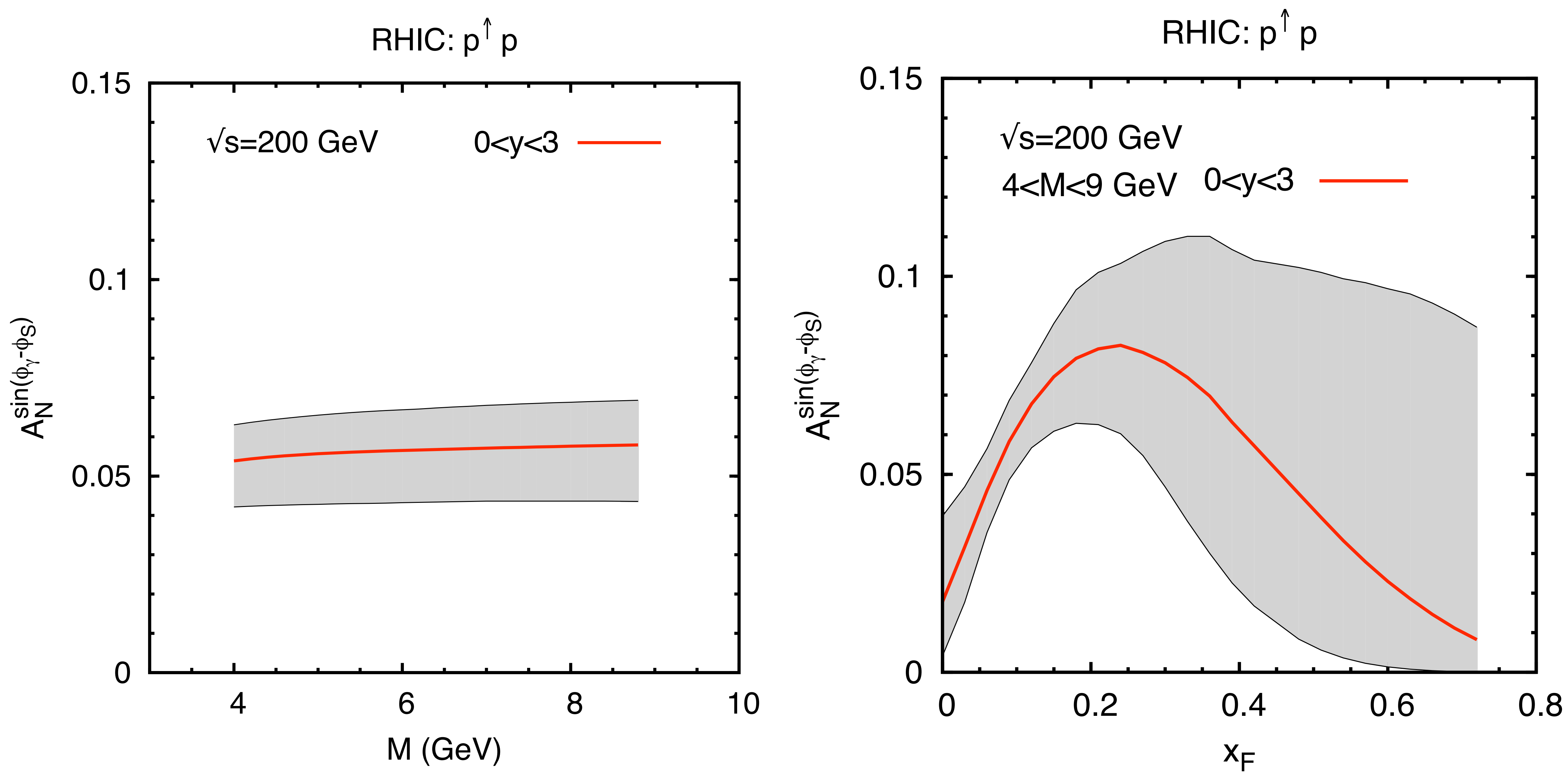
- Careful about the frame: $A^\uparrow + B \to \left[\gamma^* \to \ell^+\ell^-\right] + X$
  - In A-B CM frame: $A^\uparrow$ along z-direction, B is opposite to it. "up" (↑) polarization direction is along y-axis



➡ $A_N^{\sin(\phi_\gamma - \phi_s)} = -A_N > 0$

Predictions from Anselmino's parametrizations: weighted

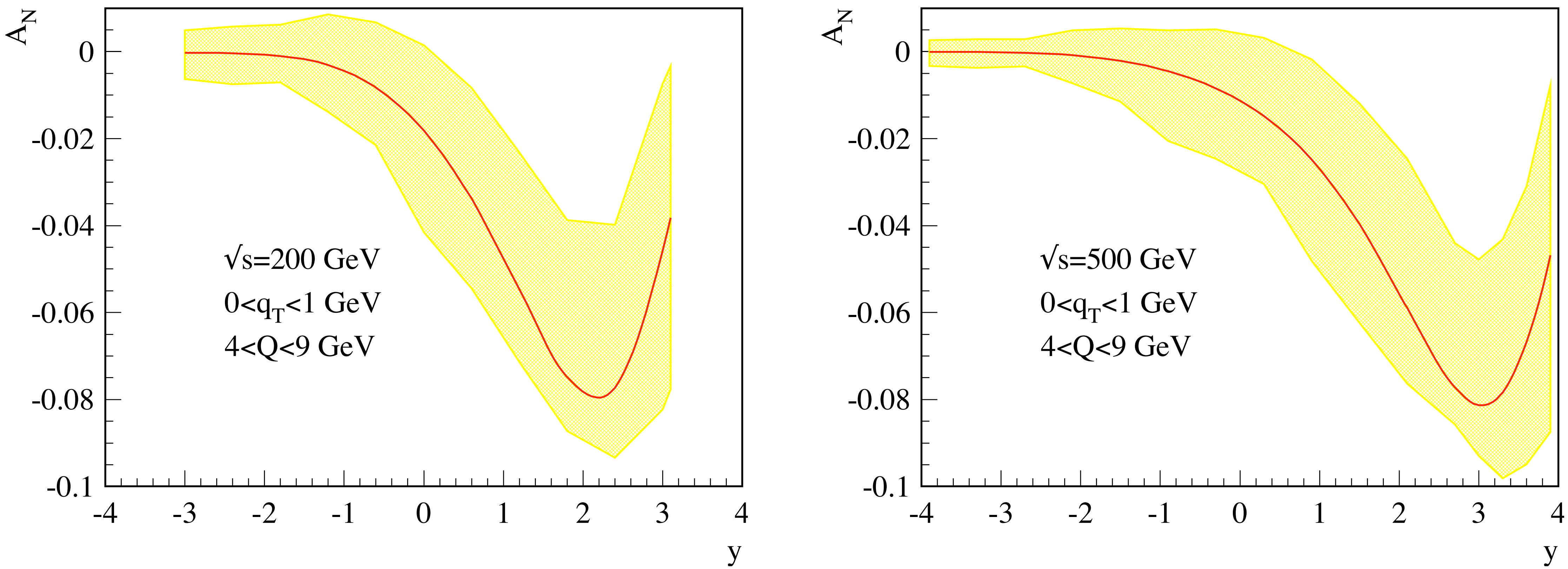
- Uncertainty band: 1-σ error of the fitted parameters in Sivers function



Anselmino,et.al, PRD79: 054010 (2009)

Rapidity dependence at 200 and 500 GeV: unweighted

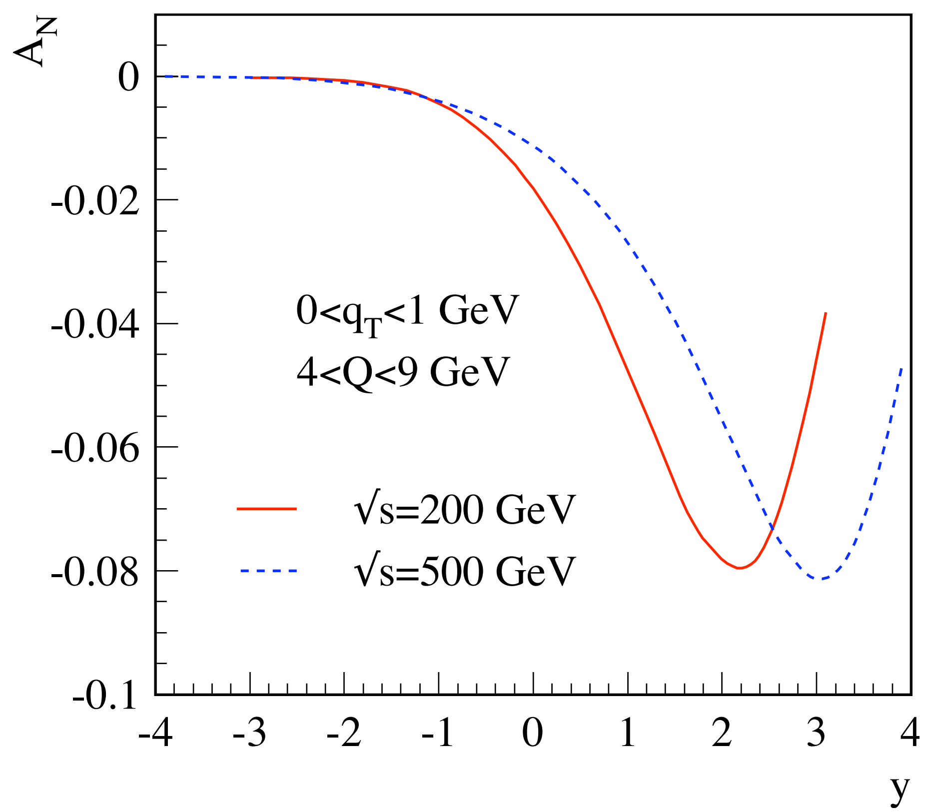
A_N ~ 2-3% in mid-rapidity y=0

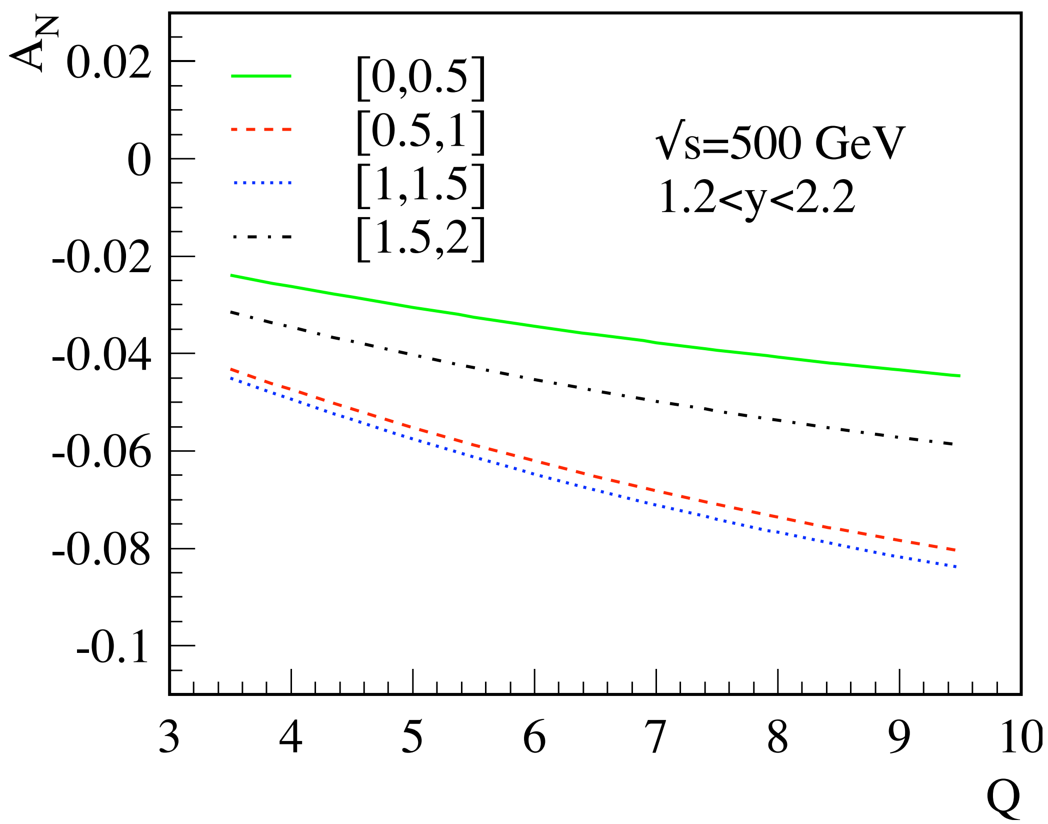


Kang, Qiu, PRD81: 054020 (2010)

More predictions for RHIC

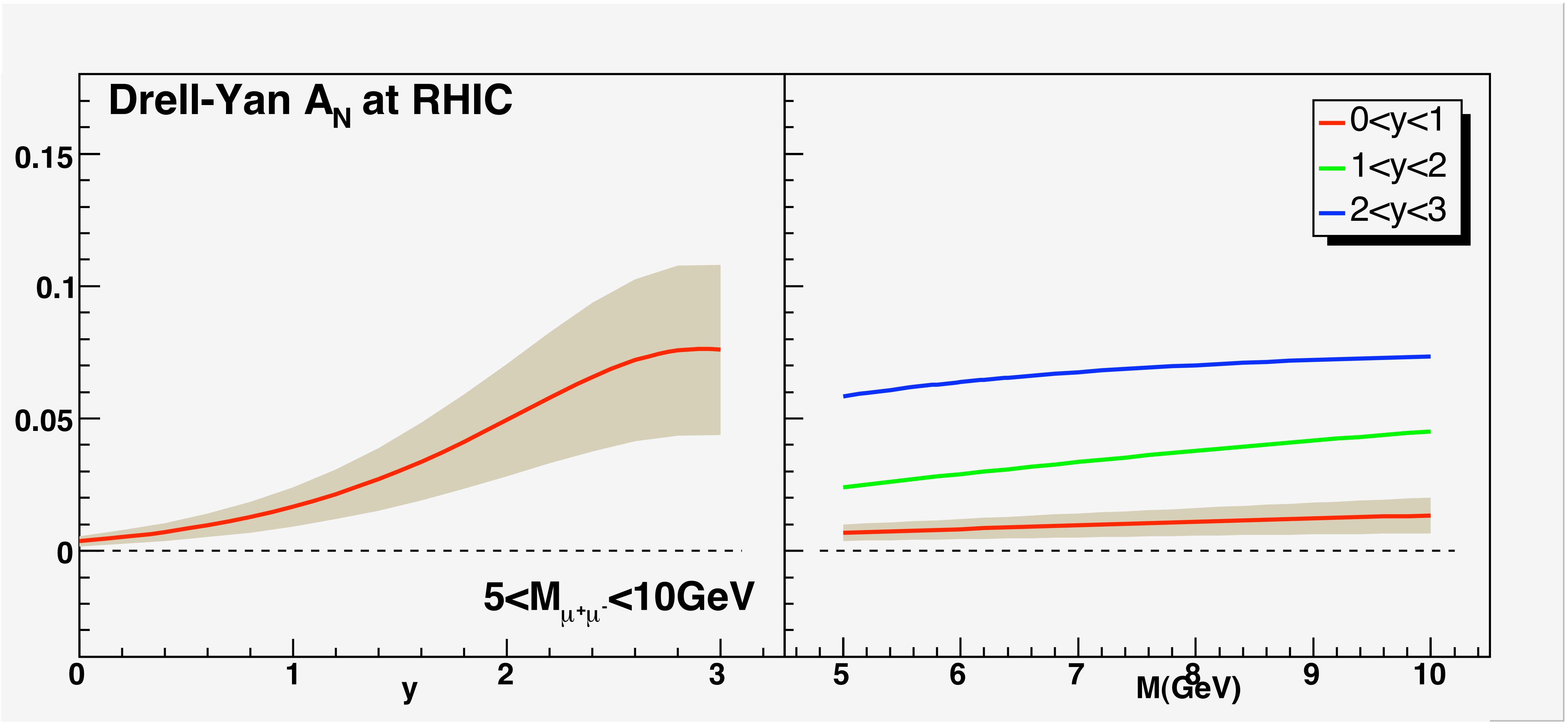
- Possible at RHIC at 500 GeV run?
  - 200 GeV might be difficult: not enough DY events
  - 500 GeV seems possible from simulations





Different parametrization of Sivers functions - I

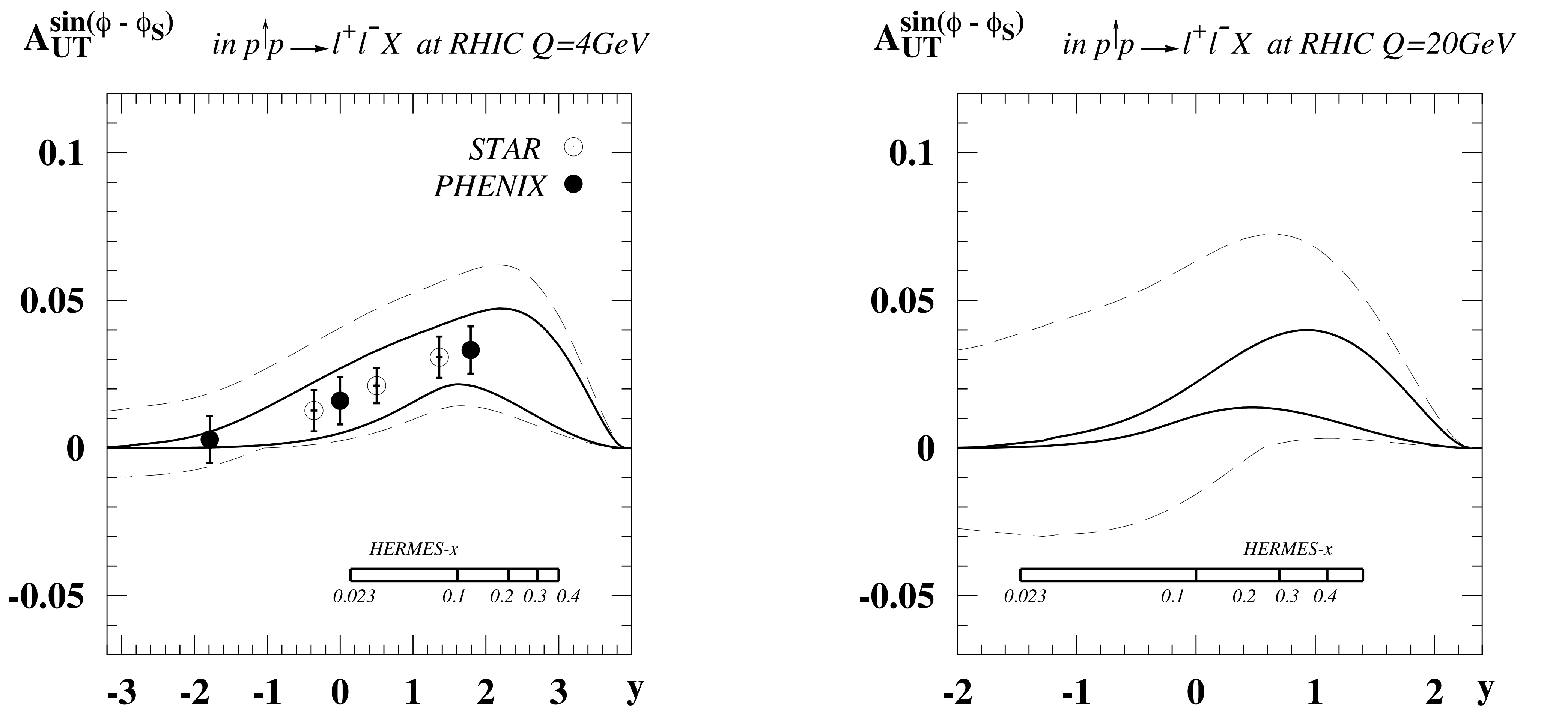
- Prediction from Yuan and Vogelsang: sign convention different



Vogelsang, Yuan, PRD72: 054028 (2005)

Different parametrization of Sivers functions - II

Collins, Efremov, Goeke, Menzel, et.al 2006



- Error band: 1-σ uncertainty of the fit of Sivers function
- Size is consistent with different parameterization

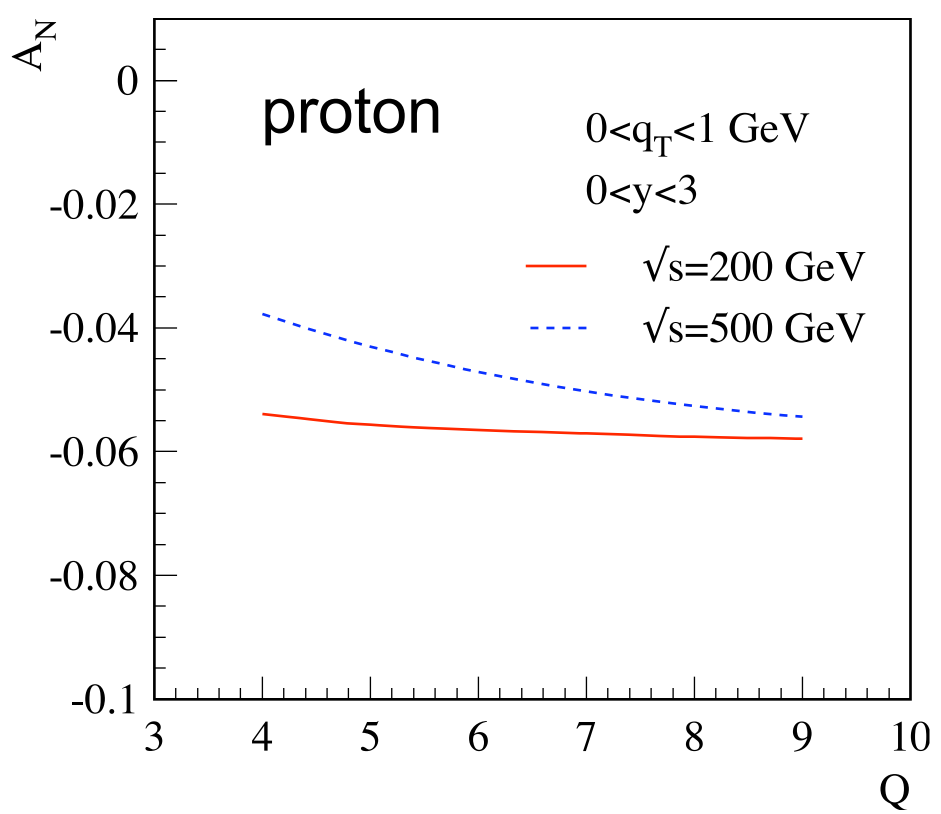
Use polarized neutron: advantage

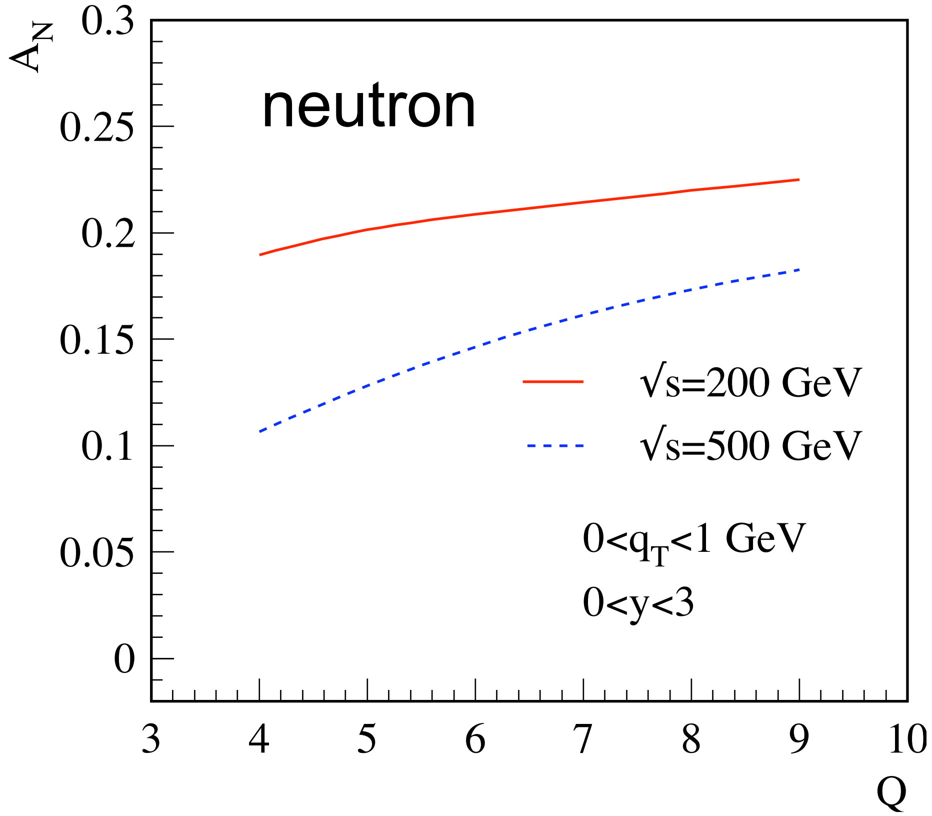
- Sign will be opposite to the proton case

$$A_N = \frac{\sum_q e_q^2 \int \Delta^N f_{q/A^\uparrow}(x_1, \mathbf{k}_{\perp 1}) f_{\bar{q}/B}(x_2, k_{\perp 2})}{2\sum_q e_q^2 \int f_{q/A}(x_1, k_{\perp 1}) f_{\bar{q}/B}(x_2, k_{\perp 2})} \propto \frac{4}{9}\Delta^N u_{\rm neutron} + \frac{1}{9}\Delta^N d_{\rm neutron}$$

$$= \frac{4}{9}\Delta^N d_{\rm proton} + \frac{1}{9}\Delta^N u_{\rm proton}$$

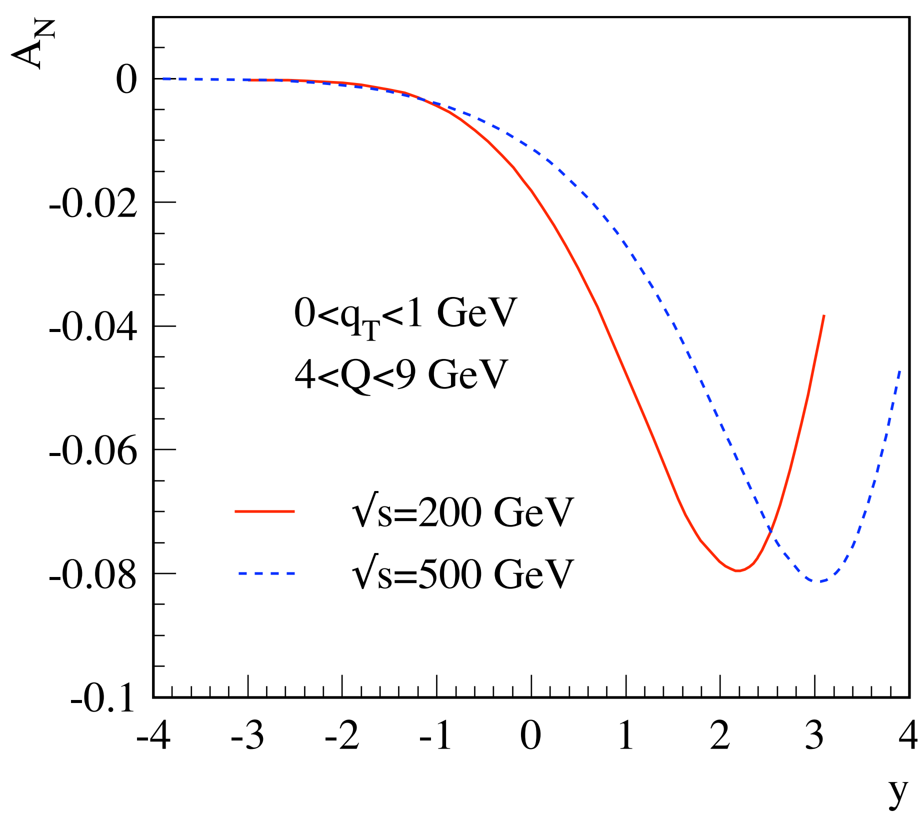
  - d-Sivers is positive, $A_N>0$
  - d-Sivers is slightly larger, at the same time, it gets enhanced more by 4/9 compared with u-Sivers, thus the size of the asymmetry will be much bigger than the proton case



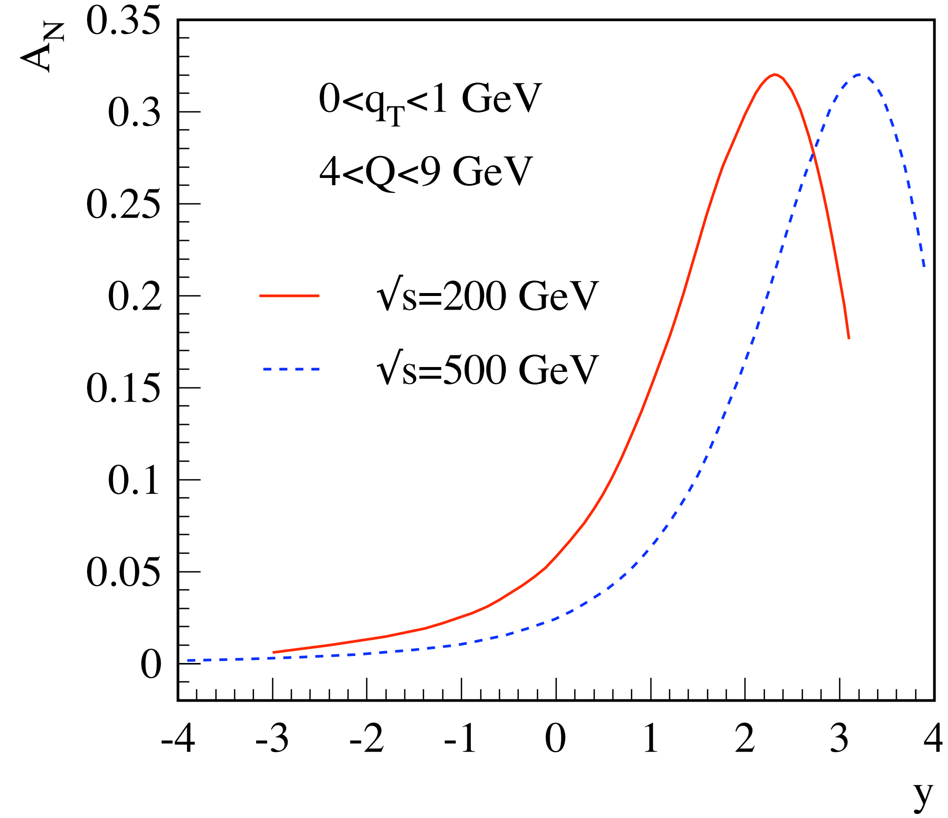


Rapidity-dependence of the asymmetry

- Positive and much larger asymmetry for He-3



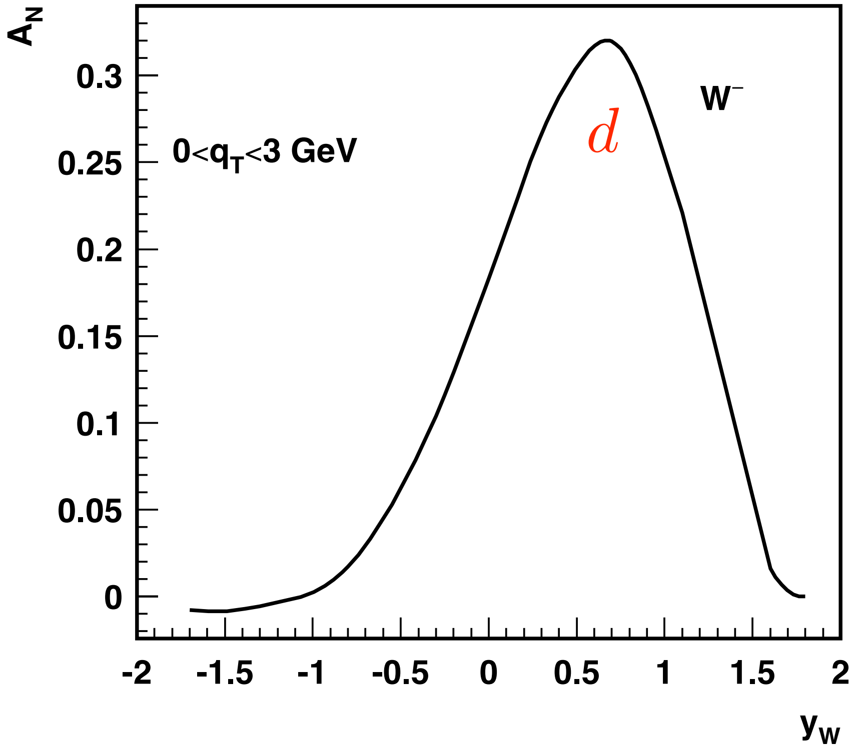
proton

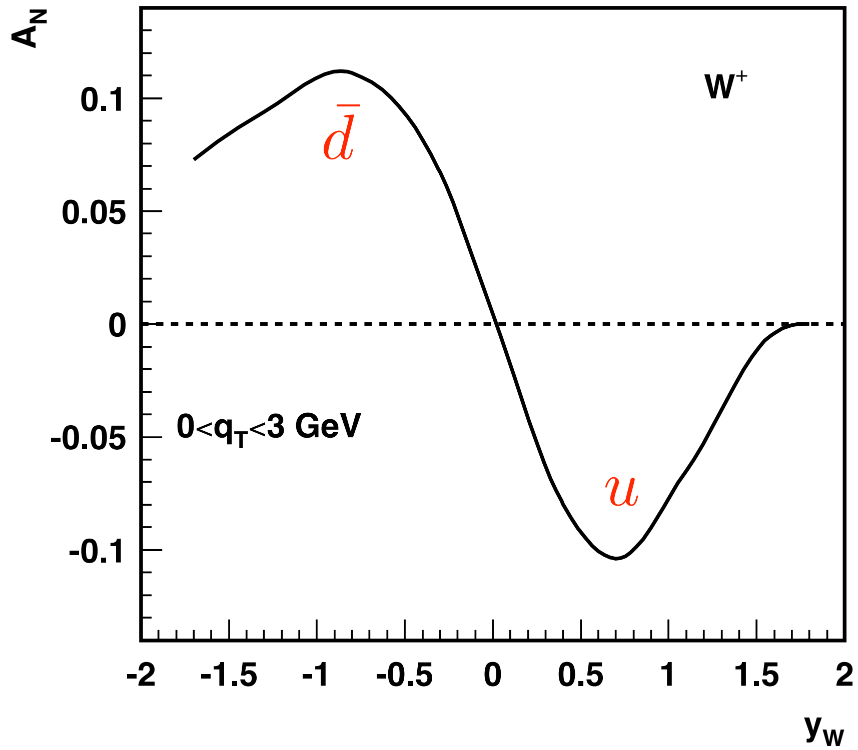


neutron

Some predictions for SSA of W bosons: pp@500 GeV

- W+ and W- could probe different flavor of u and d Sivers function

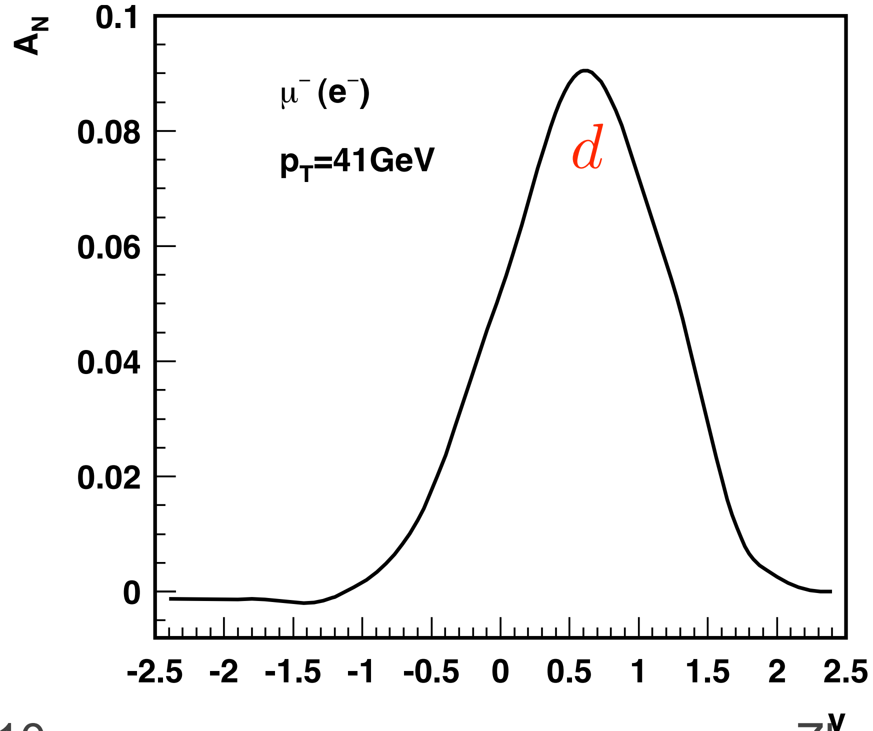


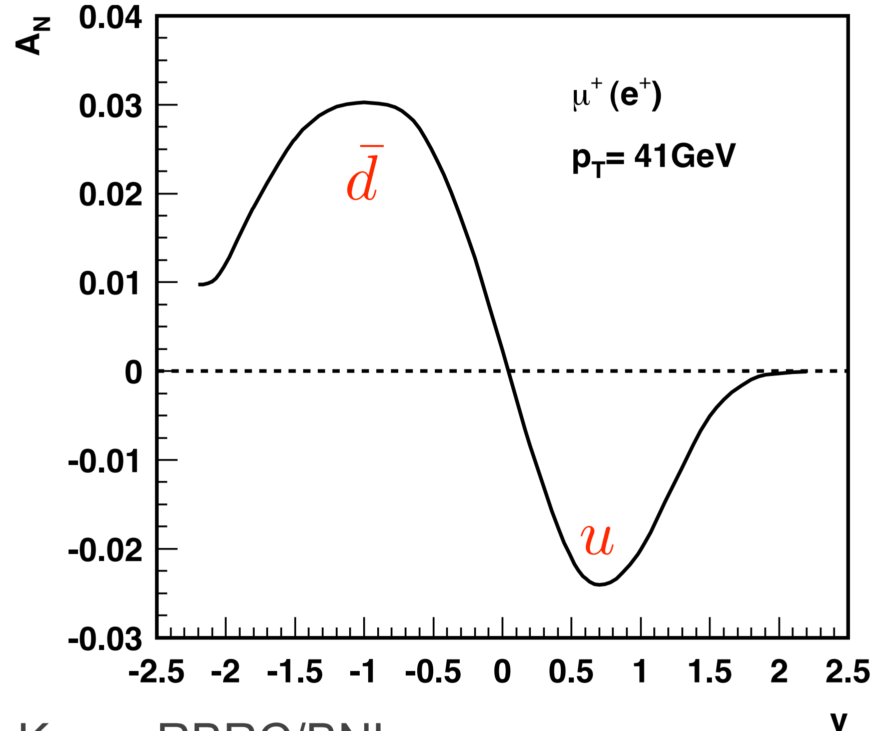


Kang, Qiu, 2009

Zhou, Metz, 2010

- SSA of leptons decayed from W: similar feature but diluted

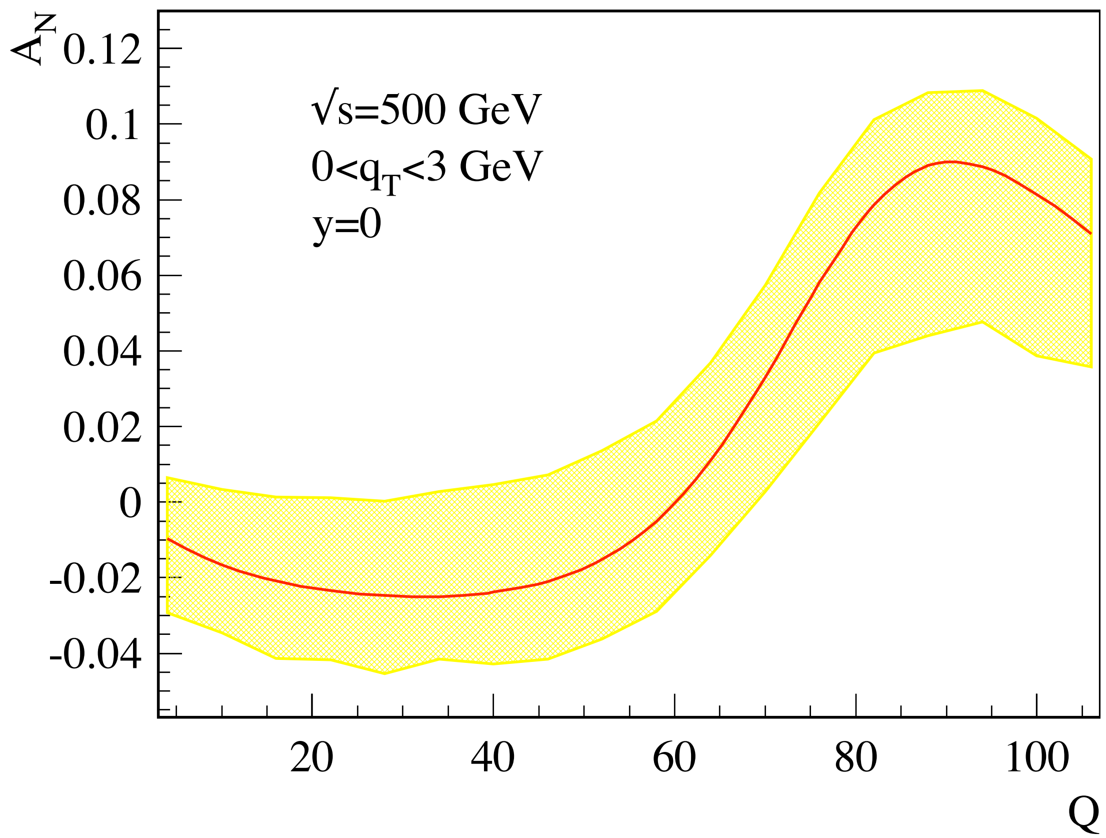


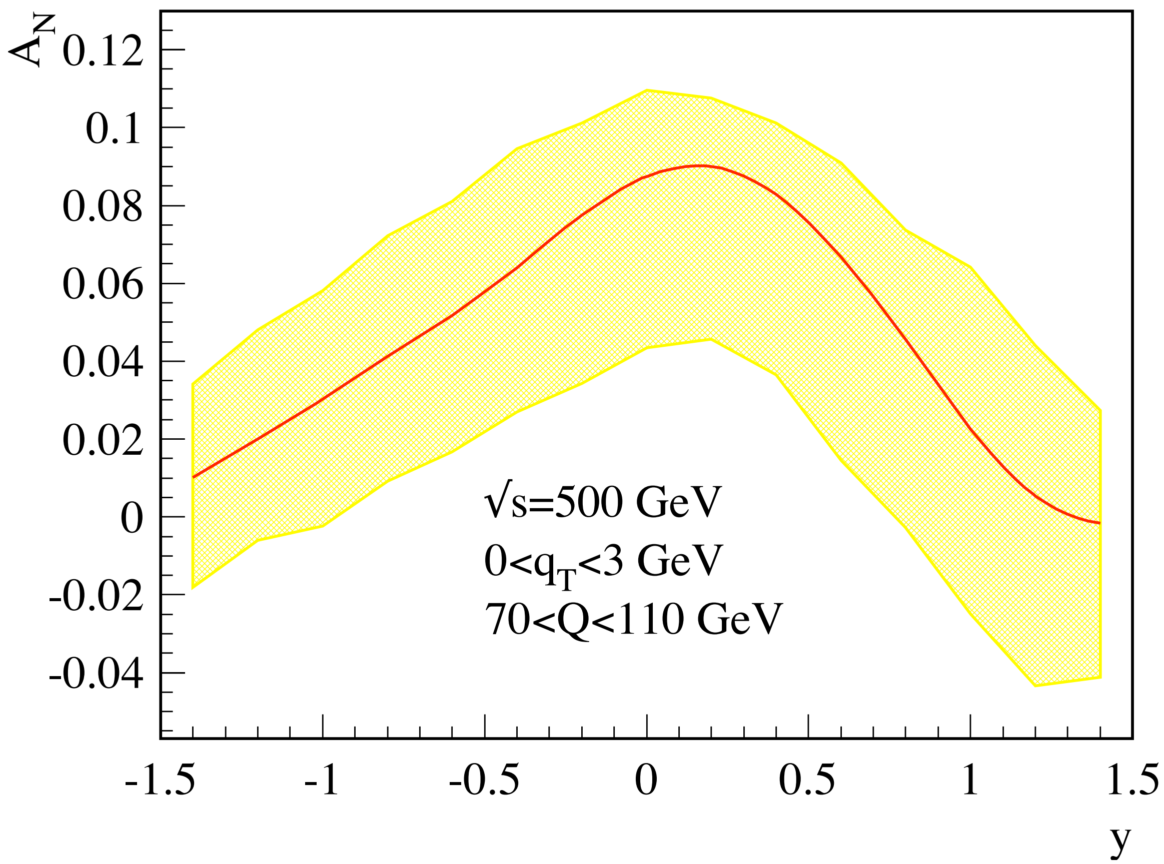


SSA of Z boson at RHIC: test relative sign of u and d

- Why Z boson: change from virtual photon to Z boson, the weight of the u and d-Sivers function changes, the sign of A_N changes

Kang, Qiu, PRD81: 054020 (2010)





- Different weights: $e_q^2 \Rightarrow v_q^2 + a_q^2$

$$
\begin{aligned}
v_u &= \frac{1}{2} - \frac{4}{3}\sin^2\theta_W \qquad a_u = \frac{1}{2} \quad \Rightarrow \quad v_u^2 + a_u^2 = 0.29 \\
v_d &= -\frac{1}{2} + \frac{2}{3}\sin^2\theta_W \qquad a_d = -\frac{1}{2} \quad \Rightarrow \quad v_d^2 + a_d^2 = 0.38
\end{aligned}
$$

Slide from “STAR Decadal Plan” by Carl Gagliardi

- The situation is not clear for W and Z productions

Other closely related measurements

- A_N for *W* production
  - Only measure the electron (or muon)
  - Can preserve significant sensitivity if measure just above the Jacobian peak with good p_T resolution
    - Not clear whether we can achieve sufficient resolution or not
- A_N for *Z* production
  - Very easy to interpret
  - **Very small** cross section !!!
  - Not clear if this is practical or not

Consequences for DY measurements

- Test the sign change of the Sivers functions between SIDIS and DY process, what are we really testing?
  - TMD approach to the SSAs
  - QCD TMD factorization
  - Our current understanding on the mechanisms of the SSAs
- If fails:
  - No sign change: our understanding for the SSAs is not complete, or not understood at all?
  - $A_N \sim 0$: Sivers is not the dominant effect for the SSAs, what's wrong with the HERMES, JLAB data? (Only COMPASS is correct?)
  - A_N is what we expect: so we are happy?
- Connection between SIDIS and pp data: talk at tomorrow afternoon

See Sivers' talk for more complete lists

Summary

- Sign change of Sivers function between DY and SIDIS is the most critical test for our current understanding of SSAs
- Let's hope we have this result as soon as possible

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Thank you